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GEOLOGY AND ORE DEPOSITS OF RED CLIFF, COLORADO.

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INTRODUCTION.

Much attention has of late been given to the deposits of Leadville, particular interest being shown as regards the relation of fissure veins to blanket deposits in that district. At Red Cliff the conditions of deposition are similar to Leadville and, as in Leadville, there are fissures and blanket deposits. In Red Cliff, however, it was possible to determine the relation of the fissure veins to the blanket deposits, and it is this point which is the item of principal interest in the following paper.

LOCATION.

The Red Cliff or Battle Mountain District (altitude 8,600 feet) is located in the southeastern part of Eagle County, Colorado, about 20 miles north-northwest of Leadville, and 75 miles south of west from Denver. The district lies on the Pacific slope 12 miles northwest of Tennessee Pass (altitude 10,229 feet) on the Continental Divide, and comprises the towns of Red Cliff and Gilman, which have a combined population of about 400. Red Cliff is the railway station for both towns and is on the main line of the Denver and Rio Grande. The town of Red Cliff is

situated in the bottom of the Eagle River Cañon while Gilman lies on the shoulder of Battle Mountain 3½ miles distant.

TOPOGRAPHY.

The Sawatch Range lies to the west and the Mosquito Range to the east of the town. The distance between the two ranges is about 25 miles. The region in the immediate vicinity of Red Cliff has been deeply dissected by the erosion of the Eagle River which, aided by tributaries, notably Homestake Creek, has cut through the sediments into the granite forming a precipitous cañon. Glacial erosion has modified the topography, particularly in the vicinity of Homestake Creek.

PRODUCTION.

During time for which exact statistics[1] are available (1904–1912) Eagle County, of which Red Cliff is the principal district, produced 143,749 tons of ore valued at $2,502,387, which based on an average value would be $17.41 per ton.

Previous to 1904 no exact statistics are available[2] so that it is impossible to estimate the production prior to that date. During the 80's and 90's many properties were producing with regularity and the value of the tonnage produced previous to 1904 must have been much greater than that mined from 1904 to 1912.

GEOLOGY.

General Features.

The district is everywhere covered by sediments save in the cañon of the Eagle River and valley of Homestake Creek where the pre-Cambrian granite basement has been reached by erosion. The strike of the sediments is on an average N. 45° W., and the

[1] Mineral Resources, U. S. Geol. Survey, 1905, p. 199; 1906, p. 215; 1907, Pt. 1, p. 253; 1908, Pt. 1, p. 378; 1909, Pt. 1, p. 311; 1910, Pt. 1, p. 410; 1911, Pt. 1, p. 540; 1912, Pt. 1, p. 677.

[2] Mineral Resources, U. S. Geol. Survey, 1882, pp. 310–311; 1883–4, p. 422; 1885, p. 255; 1886, p. 144.

dip 15° to the northeast. In the eastern part of the area the dip lessens considerably, finally becoming almost flat. To the west where the sediments lie on the granitic shoulder of the Sawatch

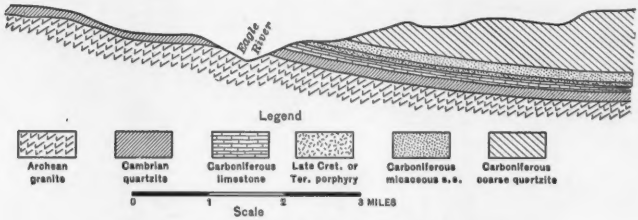


FIG. 1. Structure section at right angle to strike.

Range the dip steepens somewhat, in some places reaching 30°. In this portion of the area the granite is overlain by the Cambrian quartzite, the remainder of the Paleozoic beds having been removed by erosion. On the east of the cañon, however, nearly all of the Paleozoic section is present. From the amount and direction of the dip it is seen that the section has an aggregate thickness which approaches 5,500 feet.

Pre-Cambrian.

The basement upon which the sediments rest is a pre-Cambrian biotite granite. It varies considerably in the relative amounts of its primary constituents, which, however, are always quartz, biotite, orthoclase and microcline, with albite, magnetite, pyrite and apatite as accessories. In texture the rock also varies to some extent though generally medium grained (average size of grain 1–2 mm.), and is sometimes decidedly porphyritic with phenocrysts of orthoclase up to an inch in length. In other places, notably the valley of Homestake Creek, the rock has a decided gneissoid structure. In thin section the rock is seen to be a biotite granite with large fresh, strongly pleochroic flakes of biotite, rounded quartz grains and feldspars consisting of orthoclase, microcline and albite, the latter only present in sub-

Columnar Section.

Carboniferous (Pennsylvanian)	Maroon Formation	Dolomitic sandstone ...	200	Calcareous member of Maroon Formation.	
		Quartzitic sandstone ...	1,700	Similar to Weber grits, fine in texture and deeper red.	
	Weber Formation	Coarse quartzitic sandstone	2,700	Weber grits. Pebbles up to ¼ inch.	
		Fine sandstone	50	Brown in color, fine in texture.	
		Micaceous sandstone ...	200	Contains much ferruginous mica. Chloritic cement.	
		Black shale	50	Calcareous Weber shales. Thin bedded.	
Late Tertiary or Carboniferous		Porphyry	100	Intrusive along bedding. Greatly altered quartz-porphyry.	
Carboniferous (Mississippian)	Leadville Limestone	Gray limestone	100	Dolomitic limestone.	Limestone Ore Horizon.
		Blue limestone	50	Principal ore bearing horizon of Leadville and Aspen.	

Disconformity.

Cambrian	Sawatch or Lower Quartzite	Quartzite.	30		
		Shaly sandstone	30		
		Shaly sandstone	40		
		Sericitic quartzite	20–60	Quartzite Ore Horizon.	
		Quartzite	50		
		Sand contact	5		
		Quartzite	40	A few ore bodies at these horizons.	
		Black quartzite	40		
	Archean	Granite		Ore in fissure veins.	

ordinate amounts. The orthoclase is present in large grains, some of which show a rude crystalline outline and carlsbad twinning. Microcline of fresh appearance is generally subordinate in amount to orthoclase. The orthoclase is locally altered to sericite and the biotite to muscovite, both alterations being of small extent. At times a schistose structure is visible, and in one instance a granophyric intergrowth of quartz and biotite was seen to occur. Wherever exposed in the field the rock shows slight jointing, but the joints do not appear to have followed any regular directions. Throughout the length of the Eagle Cañon small fissures occur parallel to one another and having a general strike of N. 70°–75° E., and a dip which varies from 60° southeast to vertical. These fissures are due to faults of very small displacement, not exceeding 1–2 feet, and in the majority of cases much less. They are distributed the length of the cañon 100 to 300 feet or farther apart, though frequently two or three will occur close together. The fissures are often occupied by veins which, while yielding some ore, are as a whole of no great value, and with a few exceptions prospects started upon them have been discontinued.

Cambrian.

The Cambrian is represented by a bedded quartzite which for the most part is remarkably white and pure, varying in thickness from 200 to 250 feet. Although for the most part strong and white it contains some sandy and argillaceous layers and one that is strongly sericitic. In the portion of the area west of the Eagle River this quartzite is the only sedimentary bed overlying the granite. Farther west in the Sawatch Range the quartzite finally disappears leaving the granite exposed. The position of the quartzite is explained by the uplift of this portion of the Sawatch Range after the deposition of the sediments. The sediments upon the uplifted portion were attacked much more rapidly by erosion and were removed with relative rapidity. When the quartzite was reached erosion had slackened somewhat due to decrease of elevation of the eroded sediments. It was also checked by the extremely resistant character of the quartzite which is by far the hardest rock of the series. The quartzite

corresponds closely with the Lower Cambrian quartzite of the Leadville[3] and Tenmile[4] districts.

Carboniferous.

Overlying the Cambrian quartzite are what are known as the "Blue" and "Gray" limestones, the two forming a stratum about 150 feet thick, with the lower member or "Blue" limestone about 50 feet in thickness. In composition both members are decidedly dolomitic, and in places show silicification. This latter is particularly true of the lower or gray limestone. According to S. F. Emmons,[4] this series as a whole is Lower Carboniferous and Mississippian. He also correlates the formation at Red Cliff with the Blue or Leadville limestone, which is the principal ore carrier of Leadville and Aspen as well as of Red Cliff.

Above the "Gray" and "Blue" limestones, and separated from them by an intrusive mass of porphyry which will be described later, is in a thin bed, 50 feet in thickness, of a black carbonaceous, thin-bedded, shaly limestone which is but slightly dolomitic. This shale, known locally as Black shale according to S. F. Emmons,[5] is the Weber shale of Leadville[5] and Tenmile[4] and is the transition stage between the massive Lower Carboniferous limestones below and the quartzitic members above. The sandstone and quartzite beds which overlie the Weber shale make up the principal part of the section in this district and have a combined thickness of approximately 4,700 feet. The lower member of this series is a micaceous sandstone about 200 feet in thickness. It is gray in color and medium to finely granular in texture, contains much ferruginous mica and has a chloritic cement. The remainder of the section is composed of a series of sandstones some of which are quartzitic and which, because of the general similarity, will be described together. They vary in color from deep brownish red when the cement is ferruginous to whitish when

[3] Emmons, S. F., Proceedings Colo. Sci. Soc., 1886–7, Vol. 2, Pt. 2, p. 100.
[4] Emmons, S. F., Tenmile Special Folio, No. 48, U. S. Geol. Survey, 1898.
[5] Monograph 12, U. S. Geol. Survey.

it is siliceous. In other particulars they are like the bed of micaceous sandstone just described save that they are somewhat coarser and more quartzitic. The presence of a ferruginous mica is not as pronounced, but it is quite abundant as a cementing material and as part of the grain of the rock as well. This mica when examined in thin section in some cases showed the typical characteristics of muscovite, but in the majority of cases it was opaque due to iron stain. Overlying the sandstone and quartzite series is a bed of gray dolomitic limestone, the only occurrence in the district of calcareous sediments above the Lower Carboniferous. From a commanding elevation with the aid of a glass the same bed can be traced eastward beyond the limits of the area at the foot of the Gore Mountains, nine miles distant. As to correlation of the quartzitic beds above the Lower Carboniferous it is certain that the strongly muscovitic beds belong to the same horizon as the Weber Formation of the Tenmile District.[6] While feldspar is less abundant in the formation than in the Tenmile District, there is nevertheless no doubt of their identity. The beds are also considered by S. F. Emmons to belong to the Weber series.[7] Their thickness at Red Cliff is fully 3,000 feet. Overlying the Weber series, and differing but slightly from it, is another quartzitic horizon. This is composed of fairly fine quartz grains cemented with ferruginous material. Mica, though present, is greatly subordinate to the amount contained in the Weber series. This series has an approximate thickness of 1,700 feet and is topped by the bed of limestone previously mentioned. By comparison with the section of nearby regions it is seen that this last quartzitic series corresponds to the Maroon Formation of the Tenmile District[6] and is of Upper Carboniferous age. Upon this quartzite rests the limestone above mentioned. It is gray-blue in color and finely crystalline in appearance, contains a little iron, is slightly siliceous and quite strongly dolomitic. The only place this limestone occurs in the district is at the extreme eastern edge. It can, however, be traced for a considerable distance beyond the

[6] Tenmile Special Folio, No. 48, U. S. Geol. Survey.
[7] *Colo. Sci. Soc.*, Vol. 2, Pt. 2, p. 100, 1886–7.

area with the aid of the glass. Although its age is not absolutely determined it seems very probable that it is a calcareous member of the Maroon Formation, similar to those found in the Mosquito Range.[8]

As seen in the columnar section, the Ordovician, Silurian and Devonian members of the sedimentary series are lacking, a fact which is not in accord with most of the surrounding districts. The explanation must be that the sea bottom was subject to oscillations which raised and lowered the sea floor. During a part at least, if not all, of the epochs in question the region must have been a land area, and this missing part of the series, if any had been deposited before uplift, was removed by erosion.

Porphyry.

Intrusions of porphyry occur in two members of the series, in the Cambrian quartzite and along the bedding between the Lower Carboniferous Leadville limestone and the overlying bed of Weber shale. The occurrence in the quartzite which is along the railroad track a short distance above the town of Red Cliff is of indefinite, though small extent, and no prospecting has been done in its vicinity. The first mentioned and important belt of porphyry as traced in the field extends from Red Cliff to Gilman and a slight distance beyond both towns. It is about 100 feet in thickness and its outcrops are badly weathered. Unfortunately the porphyry was not available for examination underground. On the surface it is very greatly weathered and in places is bleached white. In texture it is dense with phenocrysts of quartz and greatly altered feldspar. The outcrops are jointed, the jointing in some places appears to be rudely columnar. The original mineral composition cannot be determined with certainty. Quartz is sparingly present as scattered rounded phenocrysts. Laths of feldspar are now sericitic alterations. In thin section the muscovite is seen to be derived from the biotite of the original rock. The groundmass is an aggregate of partly sericitized orthoclase and calcite. Quartz is sparingly present and

[8] Tenmile Special Folio, No. 48, U. S. Geol. Survey, p. 2.

often shows corroded edges surrounded by a ring of calcite and muscovite. This phorphyry cannot be definitely correlated with any similar formation in nearby camps. Another outcrop of porphyry, presumably the same as that just described, only less weathered, is in the railroad cut above town. It shows hornblende phenocrysts, much altered to chlorite, occurring in a light green, dense groundmass. Quartz is not abundant though consistently present. This rock has characteristics in common with the Quail Porphyry of the Tenmile District[9] though it cannot be definitely correlated with it. The latter porphyry in the vicinity of Red Cliff is spoken of as the Eagle River porphyry by S. F. Emmons[10] and is considered by him to be similar to the Lincoln[2] porphyry of the Leadville District.

Summary.

The section as a whole as seen at Red Cliff differs from Leadville only in the fact that the Silurian White limestone and Devonian Parting quartzite of the latter district are wanting. No trace of the Silurian member was found, while there seemed a possibility that the Parting Quartzite might be represented here and there in thin bedded quartzitic layers which have been considered as part of the underlying Cambrian. The thickness of the Leadville section from the base of the Cambrian upward through the Lower Carboniferous is about 600 feet, while the thickness at Red Cliff between the same limits is 400 feet. The difference is due to the absence of the Silurian and Devonian members of the Leadville series. At Leadville the Paleozoic members above the Blue Limestone have in many places been removed by erosion. In the Aspen[11] and Tenmile[12] Districts southwest and southeast, respectively, of Red Cliff, both the Silurian Yule Limestone (White Limestone of Leadville) and the Devonian Parting Quartzite are present.

At Aspen the section is represented from Cambrian through

[9] Tenmile Special Folio, No. 48, U. S. Geol. Survey.
[10] Monograph 12, U. S. Geol. Survey, p. 80.
[11] Spurr, J. E., Mon. 21, U. S. Geol. Survey.
[12] Emmons, S. F., Tenmile Special Folio, No. 48, U. S. Geol. Survey.

the Upper Cretaceous. All the horizons present at Red Cliff are represented in the Aspen section together with many which are absent in the former camp. From Cambrian through the Carboniferous the series at the two camps correspond exactly, save that at Red Cliff the Parting Quartzite (Devonian) and the Yule Limestone (Ordovician) are absent while both these formations are present at Aspen.

HISTORICAL AND STRUCTURAL GEOLOGY.

The sediments appear to have been deposited round the base of land areas of the Paleozoic sea, and contain a large amount of coarse material, which was derived from the Sawatch Range. Emmons suggests that a portion at least of the Sawatch Range must have been out of water because the sediments dip quaquaversally from the range as a center.[12] The Red Cliff District being northeast of the range the sediments dip in that direction. From Cambrian to close of Carboniferous, deposition continued steadily or at least without any serious interruption save during Silurian times when the district was evidently a land area. Shallow water conditions began with the deposition of the Weber calcareous shales and continued during the remainder of the Carboniferous and Jura-Trias while the coarse quartzites of those epochs were being laid down. Considerable oscillation of the sea bottom occurred during these times as is shown by the presence of beds of limestone interbedded with the coarse quartzites just mentioned. After the beds had consolidated a period of igneous activity set in, and porphyry sheets were intruded through and along the bedding of the sediments. During or after this period the Sawatch Mountains were slightly elevated, somewhat increasing the initial dip of the sediments, which in the case of Red Cliff is to the northeast. The first orogenic movement of the region was that which inaugurated the uplift of the Mosquito Range and the formation of the Mosquito fault.[13] This fault is in the eastern part of the Tenmile District southeast of Red Cliff. The porphyry sheets are cut by this fault which makes them of earlier age. Professor Emmons[13] tenta-

[13] Emmons, S. F., *loc. cit.*

tively held the fault to be pre-Cretaceous, which would place the phorphyry intrusions still earlier, probably accompanying the orogenic movement of Jurassic and Triassic times. However, in the Breckenridge District F. L. Ransome[14] has found porphyry intrusions in the Upper Cretaceous shales of that region. This makes the porphyries and consequently the Mosquito fault much younger than Emmons held them to be. From the above considerations Ransome holds the fault to be Late Cretaceous or Tertiary in age.

Within the district itself only slight orogenic movement is apparent. East of the Eagle River the sedimentary series has a dip of 15° to the northeast, while to the west of the river the dip is slightly greater. This uplift raised the portion of the area west of the Eagle River so that all of the sedimentary series with the exception of the Cambrian quartzite have been removed by erosion.

ORE DEPOSITS.

The ore deposits of the district are confined to a relatively small area, the largest part of which lies in the cañon of the Eagle River between Red Cliff and Gilman, a distance of about 3½ miles. The deposits may be divided as follows:

1. Fissure veins in the granite carrying principally gold and silver with some copper, lead and zinc.

2. Replacements in the quartzite consisting of zincblende and galena bodies, also narrow veins carrying gold and silver.

3. Replacements in the limestone comprising large bodies of zincblende, and considerable deposits of chalcopyrite and pyrite. In the oxidized zone a little carbonate of zinc is mined.

Deposits in the Granite.

The fissure veins have been formed along fault planes in the granite. These have already been mentioned as occurring at rather frequent, though irregular intervals and having a general N. 70°–75° E. direction and steep dip. The veins vary in width

[14] Ransome, F. L., Prof. Paper 75, U. S. Geol. Survey, p. 64.

from two or three inches up to a foot. The ore minerals are pyrite, chalcopyrite, galena and zincblende, all occurring in a gangue of quartz. In places copper staining by malachite and chrysocolla colors the vein material green. The chalcopyrite often shows a thin coating of bornite while zincblende is nearly always covered with a thin veneer of covellite. The gold does not as a rule occur native, as is shown by the absence of colors in panning samples from the unoxidized portion of the veins, while gold bearing samples from the oxidized zone will show colors without difficulty. The gold appears to be contained in the pyrite and is set free by the oxidation of the latter. Tellurides are said to be present in the district, particularly hessite which is reported to have occurred in considerable quantities in one or two mines.[15]

As to the properties working in the granite not a great deal can be said. Many prospects have been started on veins in the granite since the camp was first discovered and have been worked intermittently. The most persistent vein in the granite is that of the Whipsaw, which continues across the river and into the Bleak House, breaking up into the quartzite in the latter mine. On the Whipsaw claim this vein has been followed by a tunnel for a distance of about 400 feet and then pinched out. During its length on this property it varies from only a seam to about 8 inches in width. In the Bleak House which is northeast of the Whipsaw the same fissure vein has been mined to some slight extent in the granite, but its main production has been from the continuation into the quartzite, which will be discussed later.

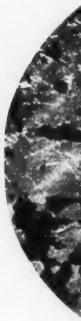
Ore Deposits in the Quartzite.

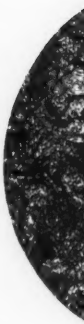
The ore-bodies of this horizon are much more important than those in the granite and in the early days were the most important in the camp. The properties in the quartzite which are now being worked are the Bleak House, Ground Hog and Champion.

[15] Pearce, Richard, *Trans. Am. Inst. Min. Eng.*, Vol. 18, 1890, p. 451.

Bleak House.

The Bleak House mine is at present entirely in the quartzite and consists of a tunnel which goes in 900 feet along the strike of the vein to the end line of the property. Adjoining ground was procured and an incline driven to follow the flat dipping zinc vein which was intersected by the tunnel at this point. The incline continues along the zinc body and has a dip of approximately 17°, a width of from 8 to 20 feet and is from 5 to 6 feet high. Above the incline the vertical fissure vein has been followed by over-hand stoping. The point of great interest in the Bleak House is the continuation of a fissure vein from the granite into the overlying quartzite, the dip changing sharply from 55° northeast in the granite to vertical in the quartzite. The vein, which is apparently a continuation of the Whipsaw, carries but small values in the underlying granite. When, however, it enters the quartzite it widens to about 2 feet and carries a large amount of argentiferous galena, some zincblende and a little pyrite. It continues on up to the surface where it outcrops above the mine in the quartzite wall of the cañon. About 150 feet above the contact of the granite and quartzite there occurs a flat-dipping vein of zincblende, dip 17° northeast, with the same general strike as the fissure vein and roughly bisected by the latter. This flat vein, although it has been relatively little prospected, appears to be 50–60 feet wide and 4–6 feet thick. Near the bottom of the vein is a parting several inches thick, which was originally thought to be the footwall of the vein. The zinc vein occurs in the quartzite at the base of a bed which is locally known as "trachyte" but which upon examination proves to be quartzite which had been altered and sericitized probably by hydrothermal solutions. In connection with the fissure vein of the Bleak House there are other points of interest to be noted. The vein occupies a fault fissure as can be distinctly seen by the slickensides on both walls. The displacement is only about 18 inches and the downthrown side is to the northwest. The quartzite immediately in the fault was greatly shattered and the subsequent deposition of the ore-body in the fissure did not





EXPLANATION TO PLATE I.

FIG. 1 of PLATE I. Pyrite replacing quartzite. This is typical of the quartzite ore deposits. Irregular outline of pyrite due to the following of interstices between quartz grains. Nicols uncrossed. × 35.

FIG. 2 of PLATE I. Sericitized quartzite from Newhouse Tun. Quartzite in matrix of sericite accompanied by pyrite (black). These quartz grains have been marginally replaced as is shown by their irregular outline. Nicols uncrossed. × 17.

FIG. 3 of PLATE I. Recrystallized dolomite limestone from Belden. This structure is typical of the limestone in the immediate vicinity of the ore deposits in the limestone. Nicols uncrossed. × 17.

FIG. 4 of PLATE I. Pyrite replacing limestone. From Iron Mask. × 17.

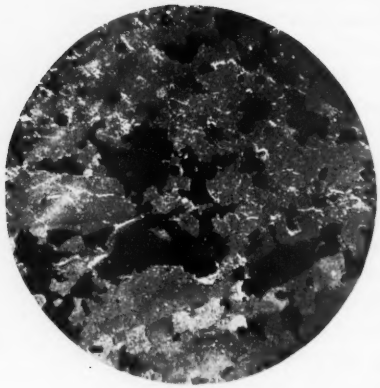


FIG. 36.

FIG. 37.

FIG. 38.

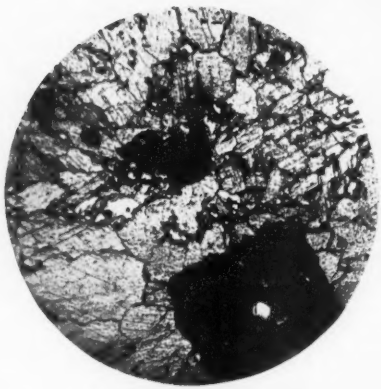
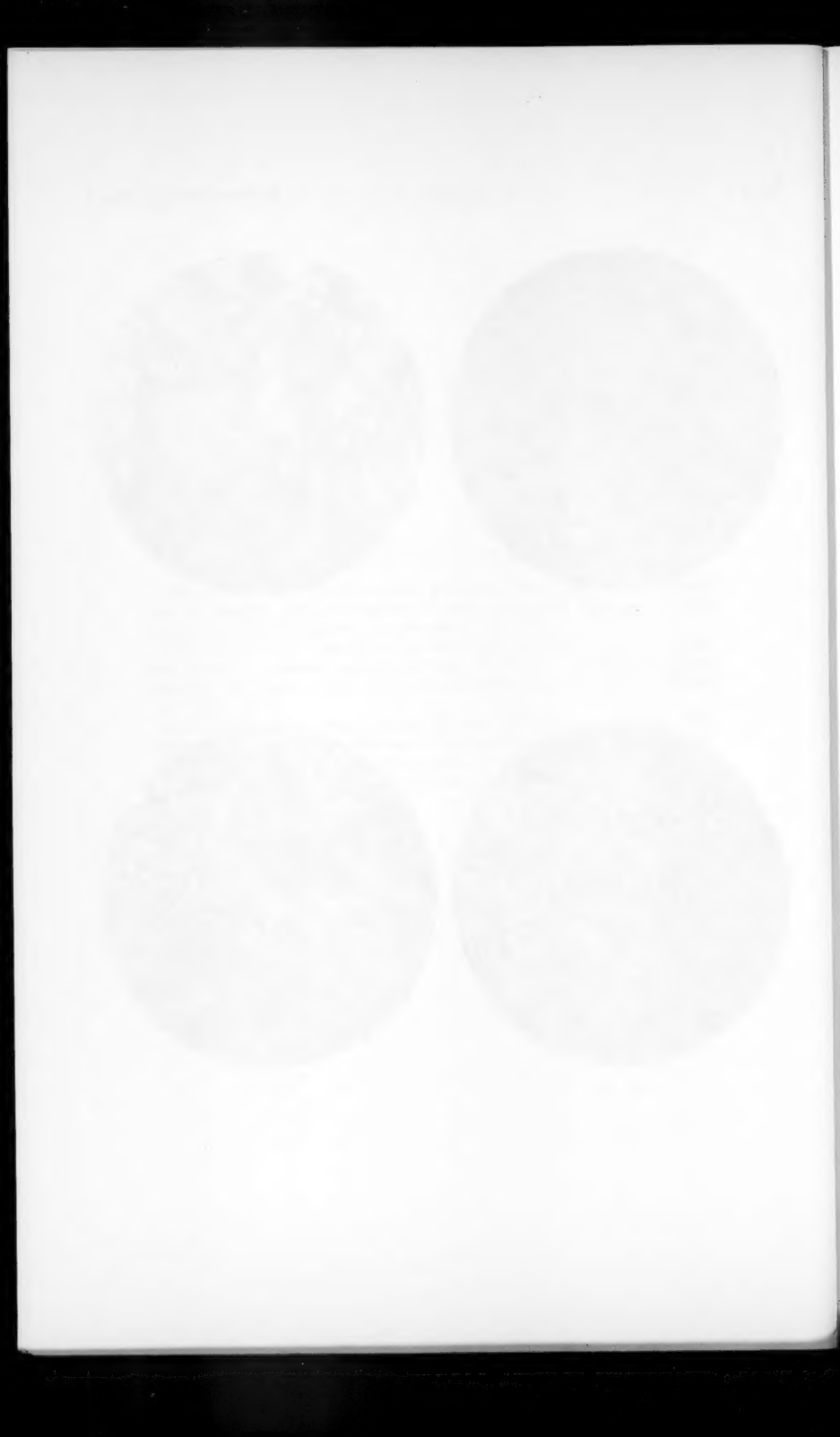


FIG. 39.



entirely fill all available openings. A specimen from along the fissure vein shows the replacement of quartzite by the vein forming material which is zincblende, galena and some quartz, the latter present as a fine silicified coating and lining of cavities. The vein carries considerable pyrite which gradually diminishes as the distance from the fissure increases. A specimen from the vein examined in thin section (Plate I., Fig. 1) showed that the grain of the quartzite has been irregularly replaced by the ore minerals. Blende accompanied by pyrite has marginally replaced quartz grains; the pyrite is of earlier formation than the blende, as is shown by the inclusions of the former in the latter.

This band of altered quartzite, which is of rather indefinite thickness, 20 to 60 feet, is found in other properties in the camp, while quartzite altered in this manner is found in many places.

Quartzite Ore Horizon (Sericitized Quartzite).

In the part of the Ground-Hog mine leased by the Success Leasing and Mining Company is another occurrence of sericitized quartzite impregnated with fine pyrite. However, of all places the breast of the Newhouse Tunnel on the Iron Mask property shows this alteration of the quartzite to the best advantage. At this point the quartzite has been altered into a greenish rock with, in places, a slightly schistose structure. When examined in thin section it is seen to be composed of rounded quartz grains and sericitic cement. The quartz grains are rounded, due to marginal replacement, in this respect being different from the other quartzites of the region whose grains are decidedly angular. The interstices are relatively large and are filled by sericite which contains some fine pyrite. The accompanying photomicrograph (Plate I., Fig. 2) gives an idea of the nature of the alteration.

Rocky Point, Ground-Hog and Champion Mines.

The Rocky Point, Ground-Hog and Champion mines, the first two among the oldest mines in the camp, have very extensive workings. The Rock Point is now idle while the other

two mines are being operated under lease. The Rocky Point is situated on the side of the cañon in the quartzite, while its workings penetrate into and under the Iron Mask, which is in the overlying limestone. The ore, principally pyrite with some chalcopyrite, is in a shattered quartzite, and is due to the mineralization of small fractures. A specimen of the ore taken at random carried 0.25 ounce of gold and 13.75 ounces silver. In the hand specimen the typical quartzite of the region is impregnated with pyrite and to a less extent chalcopyrite. This impregnation occurs along joints and cracks and gradually dies away as distance from the fissures increases. When examined in thin section the pyrite is seen to be interstitial, having worked its way in between quartz grains and in one or two instances completely surrounded them. Accompanying the pyrite is a considerable, though varying, amount of sericite, also interstitial.

The Ground-Hog and Champion are about ¾ of a mile south of the Rocky Point, though in the same horizon as the latter. The property has been operated since 1885 and is said to have more extensive workings than any other mine in the camp. The Champion is very similar to the Ground-Hog and where the geology of the latter is described, the same statements will apply to the Champion. The property is an example of a high-grade, narrow-vein mine, where the values, though high, occur with great irregularity. Rich pockets and shoots sometimes occur where the narrow veins have locally widened. The main incline goes down 1,100 feet in a general east of north direction, with a dip of about 10 degrees. At the bottom of the incline a winze, known as the Doddridge winze, has been sunk 160 feet to the granite. This winze has produced some of the richest ore of any workings in the camp, a single pocket being credited with a production of $54,000. At present the winze contains 15 to 20 feet of water so that the bottom could not be examined. Two levels have been driven from the winze at 35 and 85 feet, respectively. These follow narrow mineralized seams or fissures which have a general northeast strike. In these fissures pyrite has been deposited replacing the quartzite for a short distance to either

side of the fissure. The point of interest in connection with these crystals is the fact that they are octahedrons and cubes and that a specimen assay of them returned 21.10 oz. gold and 39.15 oz. silver per ton. A polished section of some of these crystals was examined under high magnification, 1,200 diameters, but nothing which could be identified as free gold was visible. At times the pyritization is accompanied by silicification and by impregnation with limonite.

Black Iron.—Another deposit of considerable interest, located in the quartzite just a short distance south of the Ground-Hog, is known as the Black Iron. This property could not be visited because the entrance is badly caved and on that account a first hand description cannot be given. Fortunately, however, the property was visited some years previous by S. F. Emmons from whose paper[16] the statement here given was obtained. An incline 1,200 feet in length goes down into the quartzite. Two-thirds of the way down the incline is a large sulphide body composed of pyrite and galena. This ore-body, though well within the oxidized zone, is unaltered because of its large dimensions, the alteration of the sulphides being confined to the periphery. A drift traversing the ore-body shows the progressive stages of alteration from primary sulphides at the center to the outer oxidized zone. The first result of the oxidation is the changing of the original solid mass of sulphides to a loose friable mass consisting of small crystals of pyrite. It resembles the decomposition of dolomite, producing dolomitic sand, examples of which are seen both at Red Cliff and Leadville. It is attributed to solution of the cementing material which held the grains of the original rock together. The faces of the pyrite grains were pitted as if solution were commencing. The relatively small amount of galena which occurred in this mass was oxidized to sulphate. In the next zone of oxidation green crystals of copperas, or melanterite, occurred intermixed with pyrite, which finally results in large masses of vitriol, the latter rapidly decomposing

[16] Emmons, S. F., *Proc. Colo. Sci. Soc.*, Vol. 1, Pt. 2, 1886–7, pp. 102–105.

upon exposure to the air. The next stage shows oxidation even farther advanced with the formation of a yellow ochreous substance, which appeared to be a mixture of basic sulphates together with jarosite, a hydrous sulphate of iron and potash. Fibroferrite is also said to occur.[17] This is a basic sulphate of iron, which, according to Linck, has the formula $Fe_2(OH)_2(SO)_3 + 9H_2O$. It occurs in fibrous aggregates. The end products of these various stages are considered by Emmons to be limonite, which may become hematite, and anglesite which later may form cerusite. Another point of interest in connection with the Black Iron property, which was not mentioned by Emmons, is the fact that it has produced a large tonnage of black iron (psilomelane and hematite).

Ore Deposits in the Limestone.

This is the uppermost ore-bearing horizon in the district and is overlain by intrusive porphyry sheets in the neighborhood of the ore bodies.

Iron Mask.—The most important mine in the camp, the Iron Mask, is in the limestone, together with other properties of lesser importance. It has been operated steadily for about five years. producing in the neighborhood of 100 tons of ore per day. The ore is raised along at single track incline to the surface and is then carried to the mill in the bottom of the cañon by an aerial tram. The mill, somewhat enlarged from its original capacity, now treats about 100 tons per 24 hours. The treatment consists of roasting in shaft furnaces, followed by magnetic separation and wet concentration by tables. The ore mined on the Iron Mask property is principally zinc-blende, which occurs in a gangue of recrystallized dolomitic limestone. The ore is accompanied by galena, pyrite and to a less extent chalcopyrite, both often being included by grains of sphalerite, which are dark brown to black in color due to the iron which they contain. The blende as a rule shows a rude crystalline outline, while the pyrite is generally irregular in form. The ore, a

[17] Dana, E. S., "System of Mineralogy," 1909, p. 968.

specimen assay of which returned 0.25 oz. gold and 3.00 oz. silver per ton, is for the most part free from gangue save where small cavities have been lined with a thin incrustation of siderite which contains manganese. The individual grains of sphalerite are in a great many cases surrounded by a very thin shell of this same manganiferous siderite, which seems in every way identical with that resulting from recrystallization of the limestone in the immediate vicinity of the ore deposit. Within the ore body galena is but sparingly present but at the contact between ore and limestone it is much more in evidence though not abundant. The limestone in the neighborhood of the ore deposit is greatly recrystallized and contains siderite stringers, which are about ⅛ inch wide by 1–2 inches long and have an appearance similar to miniature gash veins. If one can judge by rough qualitative tests this sideritic recrystallization appears to contain a slightly greater amount of manganese than does the unaltered limestone in the neighborhood of the ore-bodies.

Philip Argall[18] has also noted the presence of siderite in this same property, where it is described as coating crystals of galena, pyrite and blende.

Belden.—The next mine of importance in the limestone is the Belden. In this mine as in the Iron Mask the ore occurs directly beneath the overlying sheet of porphyry and also between the "gray" and "blue lime." The mine is entered by an incline in the "gray lime." The incline has a direction of south 60° east and a dip of 20° to the east and intersects the ore body between the two limestones at a distance of 900 feet from the portal. The ore is very similar to the occurrence in the Iron Mask save that chalcopyrite is much more abundant than in the former case. The blende contains pyrite in numerous small stringers practically all of which are parallel to one another. Small cavities occur here and there containing small well-formed crystals of siderite. The ore body just mentioned, which is the only one now visible because the incline is full of water below this point, is about 60 feet long, 20–30 feet wide and has been stoped

[18] *Min. & Sci. Press*, Vol. 109, No. 2, p. 52, 1914.

up to a height of 15–20 feet. A specimen assay of ore from this stope ran 0.05 ounce of gold and 2.60 ounces silver per ton.

FIG. 2. View of Eagle River Cañon.

1. Iron Mask Mine. 2. Rocky Point Mine. 3. New House Tunnel. 4. Iron Mask Mill. 5. Town of Gilman. 6. Archean Granite. 7. Cambrian Quartzite. 8. Carboniferous limestone. 9. Eagle River. 10. Main line of Denver and Rio Grande Railway. 11. Tailings pile from Iron Mask Mill.

Genesis of the Deposits.

The ores may be said to occur at three definite horizons.

1. In the limestone.
   - (*a*) At the contact of limestone and porphyry.
   - (*b*) Between the "blue" and "gray lime."
2. In the quartzite.
   - (*a*) In the sericitic quartzite ore horizon 135 feet above the granite.
   - (*b*) To a less extent between the quartzite ore horizon and the granite.

3. In the granite.
   (*a*) Ore found in fissure veins.

There is approximately a thickness of 150 feet of barren ground between the lowest bodies in the limestone, and the highest in the quartzite. There is no visible connection between the horizons of ore deposition.[19] Between the quartzite ore horizon and the underlying granite is another thickness, 135 feet, which, while not barren, contains fewer ore bodies than does the overlying ore horizon. Below in the granite are the fissure veins, which, though at times producing high grade ore, are as a whole much less valuable than either of the foregoing classes of deposits.

Theories of Deposition.

Introduction.

Before discussing the theories of deposition of the deposits at Red Cliff it will be well to establish the geological relationship of the deposits to those of other camps.

Red Cliff is on the southwestern edge of the porphyry belt which extends through Summit and Gilpin counties and on into Boulder county. Leadville, which resembles Red Cliff more closely than do any of the other nearby camps, is also located on the edge of this porphyry belt. Concerning Leadville, it is now generally agreed that the limestone ores were deposited:[20]

1. From aqueous solutions.
2. In the original forms of sulphides.
3. By metasomatic replacement of the country rock.

The points still at issue in the Leadville District are:[21]

1. "Whether the sulphide ores were originally deposited as a precipitate exclusively from meteoric or from magmatic waters, or in part from both."

2. "Whether the magmatic waters, if they were the trans-

[19] Emmons, S. F., "Geological Guide to the Rocky Mts.," 1894, p. 416.

[20] Emmons, S. F., and Irving, J. D. Bull. 320, U. S. Geol. Survey, 1907, p. 67.

[21] *Loc. cit.*, pp. 71–72.

porting agents, reached the present locus of the deposits directly from below, or whether they came up along the general channels that carried the magma of the intrusive rocks, and, where this magma had spread out in sheets between sedimentary strata, whether they followed in general the contacts between intrusives and sedimentaries or penetrated the mass of the latter along cracks and joints before depositing their load."

3. "Whether the deposits, or any part of them, were formed by contact metamorphism—that is, by waters emanating directly from the cooling intrusive bodies, squeezed out, as it were, from the solidifying igneous mass into adjoining sedimentary beds."

These are the principal points which should be remembered in connection with Leadville and with them in mind the origin of the Red Cliff deposits will be discussed.

Ore Bodies in the Limestone.—Concerning the deposits in the limestone it is possible that they are genetically connected with, and owe their origin to, the intrusion of porphyry which overlies them. The reason for this assumption is the fact that the deposits are everywhere accompanied by porphyry intrusions. The parts of the district which contain no porphyry do not, as far as was observed, contain ore-bodies. It is possible that the porphyry in cooling exuded magmatic waters which took in solution from the cooling magma the sulphides which were precipitated in the limestone. These solutions upon entering the limestone deposited zinc, copper, lead and iron as sulphides, the ore minerals being zincblende, pyrite, chalcopyrite and galena. The typical deposit of this horizon consists of abundant zincblende, accompanied by pyrite, chalcopyrite and galena. The blende is high in iron, being, in most cases, magnetic after heating before the blow-pipe, which would indicate the presence of marmatite. The individual grains, in many cases, are surrounded by a thin envelope of manganiferous siderite. From examination of thin sections it is evident that the blende was the last of the ore minerals to crystallize. It was preceded by the economic minerals that accompany it, which crystallized at about the same time. At the time of replacement, the dolomitic limestone was greatly

recrystallized in the vicinity of the ore-bodies, and contained decidedly higher percentages of magnesia and manganese than the normal sedimentary type. The porphyry when tested showed the presence of manganese, and it is likely that the manganese in the recrystallized limestone was derived from this source.

Ore-bodies in the Quartzite.—In the quartzite ore horizon the ore minerals are auriferous pyrite, chalcopyrite, zincblende and galena, and where the effect of oxidizing surface waters came into play the pyrite has been oxidized and in some places, notably at the "Ground-Hog" mine, nuggets of native gold have been recovered. In the quartzite the ore deposits are practically entirely confined to a zone of sericitic alteration, which is known locally as the "Quartzite ore horizon." This occurs about midway between the Archean granite and intrusive porphyry. It is directly beneath a zone of heavy sericitic alteration with accompanying pyritization. The sericitic zone, while varying somewhat in general aspect from place to place, is essentially the same throughout the camp despite local variations. In thin section the type slide shows quartz grains which have been marginally replaced in a matrix of sericite containing pyrite (see Plate I., Figs. 2 and 3). This sericitic zone as near as could be determined is 20 to 60 feet wide. Furthermore, the unaltered quartzite of this zone shows no different properties from that above or below this particular horizon and, therefore, it is difficult to conceive of any agent within the quartzite itself which would cause precipitation at this particular point. From this it must appear probable that precipitation was due to some influence exerted from outside. A possible explanation is the coming together of two solutions and chemical reaction between them along this particular horizon. The solution carrying the sulphide minerals would then have been ascending and the other, or what may perhaps be called precipitating solution, descending. The solution carrying the sulphide minerals is believed to have been ascending rather than descending for the reason that ore-bodies, though of lesser importance, occur all the way from the base of the Cambrian to the quartzite ore horizon 135 feet above, while between the

quartzite ore horizon and the overlying ore-bodies in the limestone, a distance of 150 feet, there is practically no ore at all. Another point of interest is the fact that rhodochrosite was found in one instance in the quartzite intimately associated, as a gangue mineral, with pyrite. This can be interpreted in two ways, either the manganese was precipitated from the descending waters which derived it from the porphyry, or it was deposited by ascending solutions which dissolved it from the granite, which also contains manganese. The ores of this horizon have a considerable range in mineral composition. They consist of zinc bodies, of which that of the Bleak House is an example, auriferous pyrite deposits as in the Rocky Point, Ground-Hog, and the majority of properties in the quartzite, argentiferous galena and black iron (psilomelane and hematite), of which at present none is mined in the district.

After the ore-bodies were deposited, they were in many instances subjected to oxidizing influences, presumably surface waters, to considerable depths. The alteration of sulphides can be traced through the various stages which in the case of pyrite and galena are limonite and cerusite, respectively.[22]

The foregoing theory of the origin of the deposits, while fulfilling the conditions imposed by the observations in the field, is not the only hypothesis which may be advanced for the origin of these ore-bodies. As an alternate theory the following will, in the light of the field evidence, apply equally well.

The intrusive porphyry was derived from an underlying and probably deep-seated magma. Following the porphyry intrusion magmatic waters ascended from the underlying magma through the Archean granite. Upon entering the quartzite ore deposition occurred in the manner already described. The formation of the quartzite ore horizon in this case must be explained by considering the quartzite at this point more favorable to ore deposition than elsewhere, but beyond this hypothesis no definite theory for a concentration of deposition at this point can be advanced,

[22] Emmons, S. F., *Proc. Colo. Sci. Soc.*, Vol. 2, Pt. 2, p. 105, 1886–7.

unless perhaps that the overlying shaly sandstone acted as a slowly permeable stratum causing partial deposition before the solutions could penetrate it. The ascending solutions now continued upward to the intrusive porphyry where replacement and deposition in the limestone occurred. Deposition of ore took place here probably because the porphyry acted as an impermeable barrier to the further upward advance of the solutions. Also the deposition was further aided by chemical reaction between solutions and porphyry.

This theory has the advantage of simplicity over the first advanced since the ore deposition is accounted for by one period of mineralization instead of two. From the evidence at hand, however, it does not seem justifiable to show preference to either one of these theories, because from the available data either one will explain the ore deposition in a satisfactory manner.

Bleak House Fissure Vein.—The next phenomenon which will be considered is the Bleak House silver-lead fissure vein, a specimen assay of which returned 0.05 ounce gold and 253.10 ounces silver per ton. This vein, while it does not throw any particular light upon any of the other deposits of the camp, is in itself of great interest due to its peculiar mode of occurrence, which has been already mentioned in this paper. Its abrupt change of direction to vertical upon entering the quartzite may be explained on the theory that, the inclined fault fissure upon entering the quartzite would break at right angles to the bedding as a plane of least resistance and since the bedding is horizontal would cause a vertical fissure. An analogous case would be that of a thin piece of wood which will break at right angles no matter if the force which causes the rupture be perpendicular or oblique.

The next point of interest in connection with this fissure vein is the fact, which has already been noted elsewhere, that it cuts the flat zinc body of the Bleak House. At the point of intersection the vein widens very much as compared with its normal width and has a very ragged outline, so much so in fact, that if it were not for the vein above and below the zinc body, it would be difficult to trace the former in the latter. The zinc body, how-

ever, is faulted slightly, about 18 inches, the down throw being to the northwest. It must, therefore, have been in place prior to the formation of the fault in which the silver-lead vein material was later deposited. From this fact it seems probable that the fissure veins of the district are younger than the blanket deposits.

Fissure Veins in the Granite.—The fissure veins of the underlying granite are similar to the Bleak House except that they do not appear quite as strong, and do not apparently continue into the overlying quartzite. In passing from the quartzite ore deposits to those of the granite there is an abrupt change in value, for the fissure veins as a whole are relatively poor. The ore minerals of these veins are pyrite, chalcopyrite, galena and zinc-blende, this latter generally coated with covellite, and occasionally some malachite and chrysocolla, the whole accompanied by a small amount of quartz gangue. The minerals were apparently precipitated from an alkaline solution which did not precipitate all of its mineral content till the quartzite was reached.

SUMMARY.

The origin of the deposits may be briefly summed up as follows:

First Theory.

1. The deposits in the limestone were derived from the overlying porphyry, the minerals being carried into the limestone and replacing it through the agency of the magmatic solutions exuded from the porphyry.

2. The deposits of the "quartzite ore horizon" in the quartzite are due to the reaction of the ascending magmatic waters with descending waters which resulted in general deposition and zone of sericitic alteration.

3. The fissure veins in the granite owe their ore to ascending alkaline solutions, which upon entering the quartzite deposit rich ore. They are later than the blanket deposits.

Second Theory.

1. Both limestone and quartzite ore bodies are the result of one period of mineralization. The ore-bearing solutions ascended from depth, deposited at the quartzite ore horizon due to the peculiar favorability of this horizon to precipitation. They then continued upward without further deposition till the porphyry was reached, this later acted as an impermeable barrier and caused further precipitation.

2. The fissure vein deposits resulted from the precipitation by ascending alkaline solutions, which upon entering the quartzite deposited rich ore. They are later than the blanket ore-bodies.

OCCURRENCE AND ORIGIN OF THE BAUXITE DEPOSITS OF ARKANSAS.

W. J. Mead.

During the past five years the state of Arkansas has produced annually over 80 per cent. of the bauxite mined in this country. This figure is due to the concentration in Arkansas of the mining operations of the American Bauxite Company, the principal producer of bauxite in America, and bears no relation to the state's rank from the standpoint of bauxite reserves. The major part of the production comes from what is known as the Bauxite District, sometimes called the Bryant District, lying about 18 miles southwest of the city of Little Rock and covering an area of about 12 square miles in Bryant township of Saline County. The second and less important district is known as the Fourche Mountain District, lying immediately south of the city limits of Little Rock in Pulaski County and embracing an area somewhat larger than the Bauxite District. The two areas are about fourteen miles apart.

Fig. 3. Outline map of Arkansas showing locations of bauxite districts.

The bauxite is all mined from open pits. The overburden is in some cases removed by steam shovel, but the uneven nature

of the bauxite, together with the close grading required make it necessary to mine all of the ore by hand.

The major portion of the bauxite is used for the production of metallic aluminum, for which purpose it is refined at East St. Louis, Ill., and reduced at Niagara Falls. A considerable tonnage is used for the manufacture of the artificial abrasive, alundum, and some of the bauxite which is especially low in iron is used in the preparation of various salts of aluminum.

The geology of the region has been described in the reports of the Geological Survey of Arkansas.

The bauxite deposits were discovered by Dr. Branner when he was state geologist of Arkansas and described by him at that time.[1] Dr. Branner recognized the genetic relationship between the bauxite and the eruptive syenite. He did not believe, however, that the bauxite was the result of the alteration of the syenite, but thought that it was derived in some manner from the syenite and precipitated as a type of chemical sediment in a shallow sea, explaining the pisolitic structure by action of the waves on a sea beach.

In connection with a very excellent work on the igneous rocks of Arkansas,[2] Dr. Williams suggested the possibility of the bauxite being an alteration product of the syenite, but believed this improbable and proposed as a more plausible theory the formation of the bauxite through hot spring action by the heated waters from the still hot igneous rocks.

The most complete report on the district is the one made for the United States Geological Survey by Dr. C. W. Hayes[3] from a field study made in 1900. It includes general and detailed maps of both the Saline and Pulaski County districts, descriptions of the bauxite as to texture, chemical and mineralogical composition, a discussion of the origin of the bauxite, and estimates of

[1] Branner, Dr. John C., "Bauxite in Arkansas," *American Geologist*, March, 1891, Vol. 12, pp. 181–183. "The Bauxite Deposits of Arkansas," *Journal of Geology*, 1897, Vol. 5, pp. 263–289.

[2] Williams, Dr. J. Francis, "Igneous Rocks of Arkansas," Annual Report, Geological Survey of Arkansas, 1890, Vol. II.

[3] Hayes, Dr. C. W., "The Bauxite Deposits of Arkansas," 21st Annual Report, United States Geological Survey, Pt. 3, pp. 441–472.

the tonnage of the bauxite deposits. Dr. Hayes, following Dr. Branner and Dr. Williams, thought that the bauxite deposits were the results of the action of hot springs from the still heated syenite rocks, and that they were in part a type of chemical sediment precipitated from solution in shallow salt water. His statement of the manner of origin of the deposits follows.

"The syenite of the bauxite region was intruded under a light cover of Paleozoic rocks. These were subjected to rapid erosion and the surface of the syenite was exposed. Either its subjacent portions retained a considerable portion of their original heat or a fresh supply of heat was furnished by renewed intrusions or dynamic disturbances. The region was then covered by a body of water probably cut off from the sea, and salt or highly alkaline. The alkaline waters by some means gained access to the heated portions of the syenite and dissolved its minerals. The heated waters returned to the surface heavily charged with the constituents of the syenite in solution. They were still efficient solvents, however, and acted upon the syenite at the surface, removing most of the silica along with the lime and alkalies, but leaving the alumina and depositing in place of the constituents removed about as much more alumina as the rock originally contained. Some of the alumina brought to the surface in solution was thus deposited by this metasomatic process, replacing a part of the silica removed from the syenite, but a larger part was thrown down as a gelatinous precipitate on the bottom of the water body and somewhat evenly distributed over the undulating syenite surface, at the same time acquiring the pisolitic structure and becoming mingled with the bowlders of aluminized syenite. Most of the spring exits were in the immediate vicinity of the syenite areas, so that there the water was most strongly impregnated with the various salts in solution and hence precipitation of the alumina was most rapid. Wherever the ascending solutions found their way to the surface by an isolated conduit through the Tertiary sediments already deposited, a local deposit of greater or less extent was formed. The precipitation of the alumina must have taken place almost immediately after the solution emerged from the conduit, otherwise the bauxite would have been much more widely disseminated, or even entirely dissipated, in the surrounding sediments. . . .

"The theory outlined above is the best at present available, though it is confessedly unsatisfactory and incomplete. Additional light will be thrown on the subject by a study of the various chemical reactions which are assumed to have taken place in passing from the syenite to the bauxite, and also by further study of the relations which the deposits

bear to the various associated formations. Such information will come only with the further development of the field."

As a result of recent detailed exploratory work, it is evident that Dr. Hayes's estimates of tonnage are very greatly in excess of the amount of bauxite actually present.

The deposits have been worked extensively, particularly in the Bauxite District during the fourteen years which have elapsed since the district was studied by Dr. Hayes, and now afford much information and opportunity for study not available at that time.

The writer has recently had charge of considerable detailed geological work in the districts and has had opportunity to study quantitatively the metamorphic changes involved in the formation of the bauxite. The field work covered a period of about eight months in 1912 and 1913. Approximately 18,000 acres of land were mapped in detail, for the most part in the productive portions of the districts and including all of the producing mines. In addition to the detailed mapping 1,152 test pits and 52 drill holes were put down, with an aggregate vertical footage of 35,000 feet, of which over one third was in bauxite and associated kaolinized syenite. About twenty-four hundred partial analyses (SiO_2, Al_2O_3, Fe_2O_3, TiO_2, and loss on ignition) were made of bauxite and associated clays, also several complete analyses showing gradation from syenite to bauxite.

The detailed field work and the exploration work was under the immediate charge of Mr. Julius Segall, to whom the writer is indebted for very valuable and efficient assistance. The writer is indebted to the Aluminum Company of America for permission to use information and data, and especially to Col. J. R. Gibbons, superintendent of mines and plant for this company at Bauxite, Arkansas, whose hospitality and coöperation greatly facilitated the work in the field.

GENERAL GEOLOGY.

The geological considerations essential to a discussion of the occurrence and origin of the bauxite may be briefly stated as follows. Large masses of nepheline syenite were intruded into

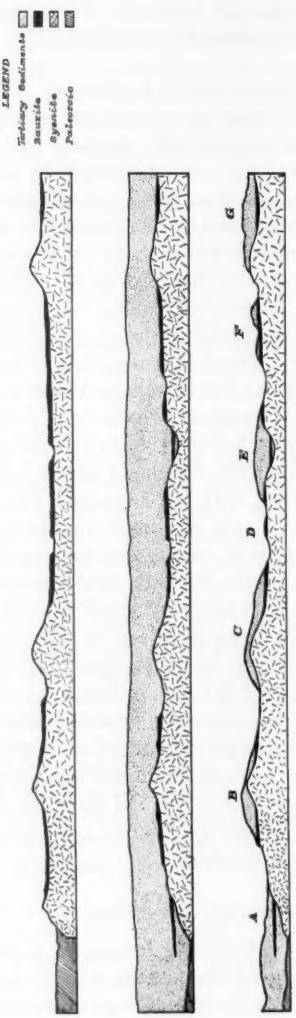


FIG. 4. Generalized cross-sections illustrating the geological history of the bauxite occurrences.

folded Paleozoic rocks and subsequently exposed at the surface by erosion. The bauxite deposits were developed on the undulating surface of the syenite by weathering, and suffered considerable contemporaneous erosion by streams. The entire area was then covered by terrestrial sediments of probable Tertiary age and consisting of clays, sands and gravels with lenses of lignitic material. The syenite areas, being more resistant to erosion, stood in relief above the surrounding areas of softer rocks on the Tertiary land surface and the bauxite deposits suffered erosion contemporaneous with the deposition of the lower Tertiary sediments resulting in the transportation of bauxite and its interstratification with sands and gravels around the border of the syenite area and in topographic depressions within it. Recent erosion has cut through the Tertiary sediments exposing the underlying igneous rocks and the bauxite deposits.

The principal events described in the foregoing are illustrated in the following series of generalized cross-sections (Fig. 4).

The first cross-section shows a mass of nepheline syenite exposed at the surface and somewhat reduced by erosion. The processes of rock decay have altered the flatter portions of the syenite to kaolinized syenite and bauxite. Streams have begun to cut valleys through the altered portions of the syenite.

In the second cross-section there has been further cutting by streams and the entire country has been completely covered by débris consisting of clays, gravels, and sand brought down by the rivers and streams from the northwest. Note in the left-hand portion of the cross-section that some of the bauxite has been carried off and deposited interstratified with the gravels and sands, and also near the center of the cross-section bauxite has been washed into a valley and is likewise interstratified with sands and gravels.

The third cross-section represents conditions at the present time. Erosion has cut through the overburden of Tertiary sands and gravels exposing syenite, kaolinized syenite, and bauxite at various places and in various relations. This recent erosion has extended down into and removed portions of the bauxite. This generalized cross-section illustrates the various modes of occur-

EXPLANATION TO PLATE II.

A typical bauxite mine near Bauxite, Arkansas. Note the dark colored lense of lignitic sand immediately above the bauxite.

rence of bauxite bodies. At the left end is a lens of bauxite (*A*) interstratified with the Tertiary sediments; to the right of this is a Tertiary hill (*B*) with bauxite exposed on both sides, but prevented from extending through the hill by a rise in the syenite surface. To the right of this is a Tertiary hill (*C*) with bauxite exposed on the right-hand side but absent on the left. Following this is a small elevation (*D*) capped with bauxite and to the right of this, a hill (*E*) of Tertiary sediments with bauxite exposed at both sides but prevented from extending continuously through the hill by a pre-Tertiary valley. In this valley is a lens of detrital bauxite interstratified with the Tertiary sediments. To the right of this is a Tertiary hill (*F*) with bauxite exposed on both sides as well as in a small valley which cuts the crest of the hill, and at the right-hand end of the cross-section (*G*) is a body of bauxite in place, completely concealed by Tertiary sediments.

THE BAUXITE DEPOSITS.

Manner of Occurrence.

The bauxite deposits may be devided into two main classes, (*a*) bauxite in place, and (*b*) transported and detrital bauxite.

The bauxite in place, as will be shown later, is a residual product of the surface weathering of the syenite and grades downward into kaolin, which in turn grades into syenite. The deposits are horizontal tabular beds of very irregular outline. This is the most important class of deposit and yields practically all of the ore now being produced.

The transported bauxite is found interstratified with the Tertiary sediments (see cross section No. 3, Fig. 2, at (*A*) and (*E*)) and represents material which was carried from its original position by streams during Tertiary times. The original bauxite beds suffered very marked erosion during Tertiary time, the eroded material being either dissipated in Tertiary sediments or, as in a few cases, laid down in lenses of comparative purity. In some instances deposits of the first type (bauxite in place) have suffered erosion or disturbance at the surface and grade upward into what is really a basal conglomerate of the Tertiary,

EXPLANATION TO PLATE III.

Photograph of a mined out portion of the Tank Mine at Bauxite. This shows the peculiarly uneven nature of the surface left on removing the bauxite. Some of the depressions have been filled with waste material.

composed of bauxite boulders. In some cases this detrital upper portion of the bauxite bed is mixed with a considerable amount of sand and rendered nonmerchantable.

Shape and Size of Ore Bodies.

Owing to the erosion which the bauxite beds suffered during Tertiary and recent time, the portions remaining have very irregular outlines and vary greatly in size. The deposits are bounded either by wedging out against a rise in the underlying syenite or by an erosional valley. The thickness of the bauxite on the whole is comparatively uniform. The maximum known thickness of bauxite is 35 feet, but depths such as this are very exceptional and local. The average thickness of merchantable ore is about 11.5 feet. The surface under the bauxite, exposed after the bauxite has been removed, is extremely uneven and irregular. This is illustrated in Plate III, which is a photograph of the mined-out portion of one of the largest mines. In places the underlying clay extends through the bauxite to the surface, and throughout the bauxite beds horses and stringers of clay are so abundant that in the average case 40 per cent. of the material handled in mining must be discarded as waste. This figure is greatly exceeded in some places. The clay horses are everywhere abundant,—they occur in every variety of shape and size, and add greatly to the cost of mining.

Physical Characteristics of the Ore.

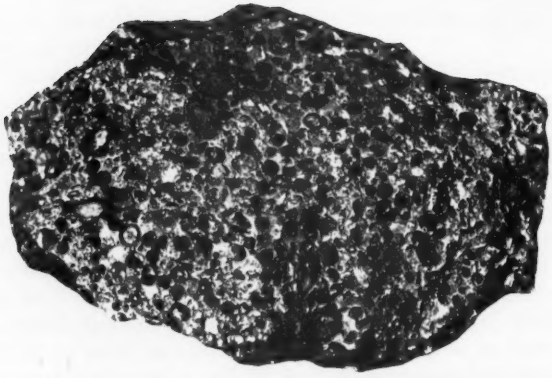
The ore varies greatly in color and texture. The prevailing color is a light buff, which grades into white, and various shades of yellow, brown, and red, depending on the content of ferric iron. There are also abundant tones of gray, grading into a very dark colored ore where it has been stained by organic material near its surface. The gray color is due in part to the presence of ferrous carbonate, which is abundant in some parts of the deposits. The degree of redness of the ore is not a safe indication of the content of iron, as some ores of a distinctly red color run comparatively low in iron,—others of a light gray color have a considerable amount of iron carbonate.

EXPLANATION TO PLATE IV.

A. A typical pisolitic or concretionary ore (sometimes called oölitic). One-half natural size.

B. Typical "sponge" bauxite. The original texture of the syenite is preserved by the pseudomorphs of bauxite after feldspar. One-half natural size.

A



B

The bauxite varies in hardness from that of a limestone or well cemented sandstone, to a soft material which can be shoveled without picking. The hard portions of the bauxite always constitute the upper part of the deposit and the soft portions are found below. The upper portion of the ore has suffered a marked induration or cementing process, which renders it hard to drill or break. All of the ore requires more or less blasting to prepare it for mining.

The bauxite has a comparatively high porosity, an average of a number of tests showing 38.5 per cent. pore space. The free moisture in the ore varies greatly with the season of the year, the ore being practically saturated during the wet season, while the upper portions of some of the more exposed deposits above the water level are well dried out during the summer months. The moisture content (uncombined water) of the ore mined varies from 5 per cent. to a maximum of 20 per cent., with an average between 12 per cent. and 15 per cent. As the ore is dried before shipment and sold on the basis of dry ore, the moisture content is not as important as in the case of ore sold on the basis of natural or "green" ore. On the average it requires 24 cubic feet of green ore in the ground to produce one long ton (2,240 pounds) of dried ore.

The ore exhibits a variety of textures. The most common type is a pisolitic or "oölitic" ore, made up of more or less spherical pisolites of bauxite, sometimes having concentric structure, in a bauxite matrix. These vary in size from microscopic to a maximum of an inch or more in diameter. Occasionally on an erosion surface of ore, the pisolites are weathered out, yielding a gravel ore. Second in importance is the ore having the texture of the syenite, commonly called "sponge ore" or "granitic ore." This bauxite preserves in varying degrees the original granitic texture of the syenite. This texture is so perfectly preserved in some instances that it is only possible to distinguish an outcrop of granitic bauxite from a weather-stained outcrop of syenite by breaking into it with a hammer.

The granitic type of ore is generally found beneath the oölitic ore and grading upward into it. Granitic bauxite grades down-

ward into kaolinized syenite, and this in turn into unaltered syenite. The granitic type of bauxite is confined to the bauxite in place, except for small rounded boulders found occasionally in the detrital upper portion of the deposits.

The third type of ore is the amorphous ore which has the texture and appearance of clay, from which it is distinguished with difficulty. In many cases a chemical analysis is necessary to distinguish a merchantable ore from kaolin. This is the least abundant of the types mentioned.

There is a complete gradation between the various types of ore. The pisolitic ore is found mixed in all proportions with the amorphous ore. One finds ore consisting largely of a "clay" bauxite with a few small pisolites grading into a bauxite made up entirely of pisolites. The pisolitic texture is distinctly more pronounced in the upper portions of the ore bodies, and the granitic type is more characteristic of the lower portions. All the types of bauxite grade into kaolin by very gradual changes so that it is difficult at all times to tell just which material to mine and which to reject.

In many of the deposits disturbance by Tertiary streams has given rise to a detrital or conglomeratic ore in the upper portion. This consists of boulders of oölitic or granitic bauxite in a matrix of smaller boulders and finer bauxite material. This may either be of merchantable grade or mixed with Tertiary sediments to such an extent as to render it valueless.

Chemical Characteristics of the Ore.

The principal chemical constituents of the ore in order of their importance are alumina, combined water, silica, ferric oxide, ferrous oxide, carbon dioxide, and titanic acid. In every deposit of bauxite, excluding the minor constituents which remain essentially constant, there is a complete gradation from the composition of gibbsite ($Al_2O_3 = 65.5$ per cent., $H_2O = 34.5$ per cent.) to the composition of kaolin ($Al_2O_3 = 39.5$ per cent., $SiO_2 = 46.5$ per cent., $H_2O = 14.0$ per cent.) (see Fig. 7). In many instances locally there is a complete gradation from bauxite to practically pure iron carbonate. This iron carbonate occurring in the bauxite

is of secondary origin, having been introduced by solutions from the overlying Tertiary sediments, which are rich both in iron and organic matter. It appears that in some instances the iron carbonate has actually replaced the bauxite, yielding local masses of comparatively pure siderite. The ferric iron is present in the form of hydrated oxide, and has been derived both from the original iron of the syenite and from the oxidation of the iron carbonate since recent erosion exposed the deposit to oxidizing conditions. The titanium was an original constituent of the syenite, and being present in minerals not easily altered, has remained. Locally in the upper detrital portions of the deposits the titanium minerals, which are dark colored and heavy, have been concentrated into bands so that portions of this detrital ore run very low in titanium while other portions in which the minerals have been concentrated run correspondingly high. The ore in place has a comparatively uniform content of titanic acid, averaging about 2.5 per cent.

In addition to the constituents above mentioned, the bauxite contains minute amounts of zirconia, barium, iron sulphide, and other accessory constituents.

The triangular diagram (Fig. 7) illustrates graphically the variation in chemical composition of the ores.

Mineralogical Characteristics of the Ore.

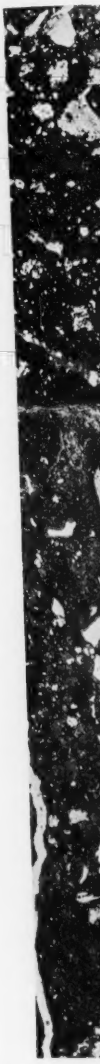
The principal mineral constituents of the ore are the two forms of hydrous aluminum oxide, which is present both in the crystalline form as gibbsite and in the amorphous form as bauxite, both approximating the formula $Al_2O_33H_2O$. It should not be inferred from this that gibbsite exists in commercial quantities as such. The two forms of the tri-hydrate of aluminum differ only in that one is crystalline and the other amorphous and neither can be mined separately.

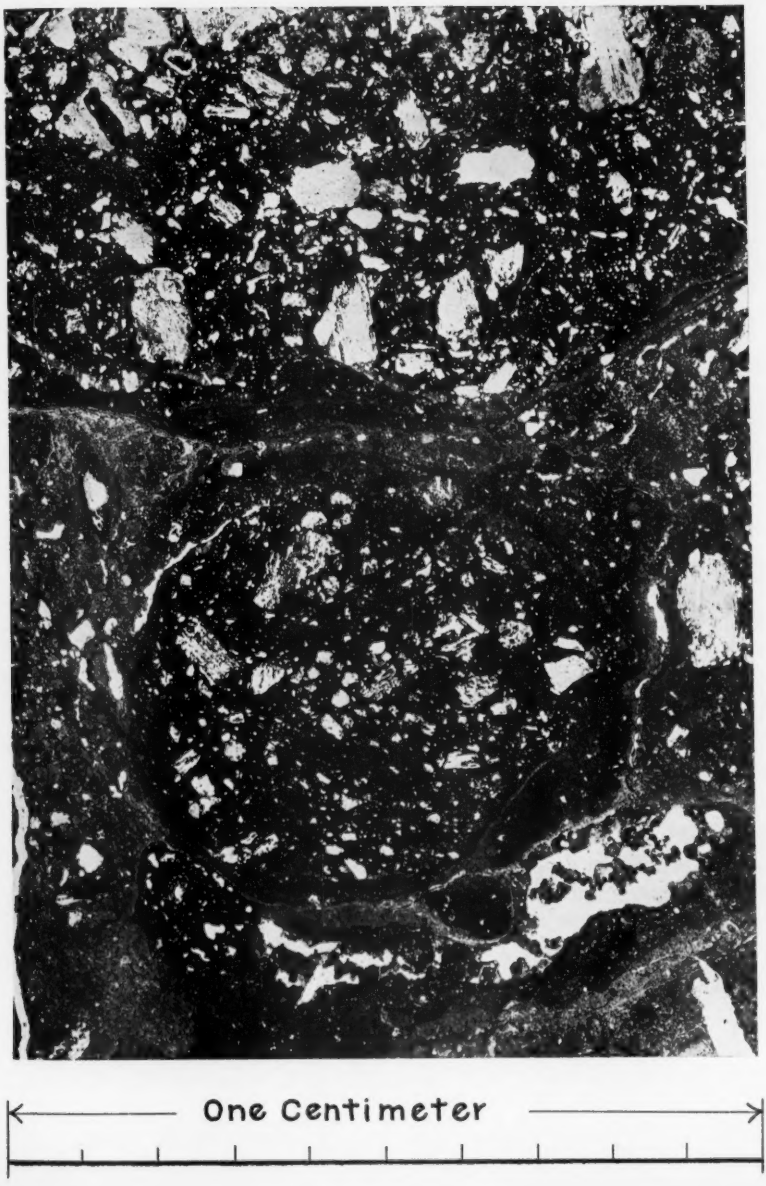
Microscopic study of thin sections of the bauxite reveals the fact that the granitic type of ore is largely composed of the crystalline form of aluminum tri-hydrate. The pisolitic type of ore is made up largely of the amorphous form, but this type of ore also contains a considerable amount of the crystalline form in

EXPLANATION TO PLATE V.

Photomicrograph of a thin section of pisolitic bauxite. Ordinary light. One complete pisolite and a portion of a larger one are shown. The darker portions are amorphous bauxite stained brown and red by iron oxide. The irregular white area in the lower right hand corner is a hole in the section. The roughly rectangular light colored areas are feldspar forms now microcrystalline gibbsite. The form and structure of the feldspars are preserved and in polarized light, effects of feldspar twinning may be seen.

PLATE V.




One Centimeter

the shape of remnants of feldspars which have been completely altered to gibbsite (Plate V.). It would seem from this that the hydrous aluminum oxide develops first in the form of gibbsite and that when it undergoes change, as in the development of the pisolitic type of ore, it tends to take on the amorphous form.

Hydrous aluminum silicates of which the most abundant is kaolinite, are second in importance. Halloysite or a closely similar compound is known to be abundant both by recalculation of chemical analyses and its observed presence in the lean portion of the bauxite. In addition to these, there are in all probability other hydrous aluminum silicate minerals which are difficult to identify because of their amorphous texture. Limonite and other hydrous oxides of iron are undoubtedly present in the ores, but it is quite probable that some of the ferric iron is combined with the alumina in the hydrous aluminum oxides.

Siderite occurs in a very irregular manner in the ores. It is found filling vugs and cavities in the ore in beautiful botryoidal and stalactitic aggregates, and also occurs in such form as to indicate that it has actually replaced portions of the bauxite. It is very evident from the manner of occurrence of the iron carbonate that it has been introduced into the ore subsequent to its formation. The Tertiary sediments contain abundant lenses of lignitic material and also have a considerable content of iron, which affords an abundant source for solutions of iron carbonate. In all of the analyses of the ores made for commercial purposes the iron was determined as ferric oxide and no determinations were made for carbon dioxide, hence no statements can be made as to the average content of iron carbonate. Titanium is present as titanite and ilmenite, and also in all probability in the form of other titanium minerals. It is quite probable that pseudo-brookite and perofskite can be identified in the ores.

In addition to the above minerals, a very interesting group of heavy accessory minerals is found in the bauxite and associated clays. These are present in small amounts, but are of considerable importance as evidence of the residual nature of the bauxite. They are easily concentrated from the bauxite, because of their high specific gravity, by crushing and panning the ore and sep-

arating by means of a heavy solution. In an incomplete examination of these minerals the following were identified: zircon, occurring in a variety of crystal forms and varying in color from white to dark brown through shades of yellow; pyrite; barite; celsian; and fluorite. In addition to the above there are other minerals which were not identified. These minerals are excellent evidence of the residual nature of the bauxite and associated clay, since the same group of heavy minerals are also found in the unaltered syenite beneath the bauxite.

ORIGIN OF THE BAUXITE DEPOSITS.

A study of the general geology, chemistry, and mineralogy of the deposits has led to the following conclusions:

1. The bauxite and associated clays are the products of surface weathering of the syenite by normal processes of rock decomposition, and are in no sense chemical sediments.

Bauxite deposits occurring on the syenite surface have developed in situ from the syenite.

The deposits developed in situ from the syenite show evidence of downward secondary concentration of alumina.

Bauxite lenses occurring interstratified with the Tertiary sediments consist of material which has been removed from its place of origin by Tertiary streams.

2. The texture of the kaolinized syenite has been essential to the alteration of the kaolin to bauxite.

3. The oölitic or pisolitic texture of the bauxite has developed in place from the granitic or amorphous types of bauxite.

Evidence that the Deposits Were Produced by Weathering of the Syenite.

(1) That there is some genetic relationship between the syenite and the bauxite is obvious from their distribution and has been recognized since the discovery of the deposits. (2) The gradation from syenite through kaolinized syenite to bauxite, is to be observed wherever a fresh cross-section is available. This gradual gradation, both chemical and mineralogical, without any sharp

break is at once suggestive of the residual nature of the deposit. (3) The preservation of the granitic texture of the syenite in the kaolinized syenite and in the granitic type of bauxite, and the preservation of feldspar shapes replaced by gibbsite in the pisolitic ore evidence the residual origin of the ore. (4) The irregular and pitted surface exposed in the bottoms of the open pit mines on the removal of the bauxite, is in the nature of an etched surface which could have been produced only by weathering, and is certainly not the type of surface to be expected beneath a sedimentary deposit (see Plate III.). (5) The gradation from bauxite through kaolinized syenite occurs not only downward to the syenite beneath, but laterally and upward to residual boulders of decomposition of syenite within the bauxite deposit. These boulders, from a foot to twenty feet in diameter, are found in all stages of decomposition, some having cores of fresh syenite and others which have been completely altered to bauxite and are represented only by boulder forms in the bauxite. They indicate in an excellent fashion the residual nature of the deposits. The occurrences of these boulders are well illustrated in Plate VI and Fig. 5.

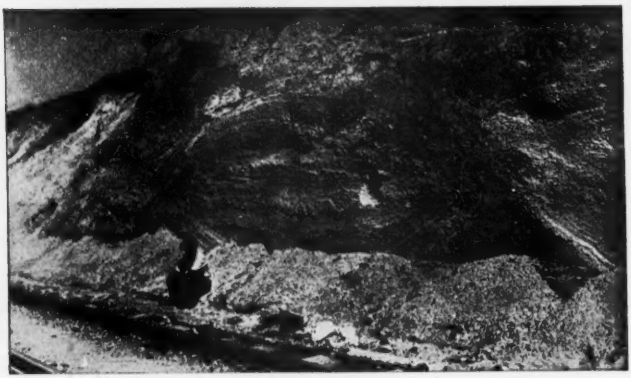


FIG. 5. This photograph shows a large boulder form produced by concentric weathering of a joint block in the preëxisting syenite. The center is kaolinized syenite and the outer part excellent "sponge" bauxite which grades into pisolitic ore toward the surface.

EXPLANATION TO PLATE VI.

Decomposition boulders in the face of an abandoned bauxite mine near Bauxite, Ark. The gradation from syenite through kaolinized syenite to bauxite is shown particularly well by the concentric weathering about the boulder in the left hand portion of the picture. The boulder to the right has been brought out in relief by disintegration and erosion since the mine was opened. It consists of kaolinized syenite with a core of fresh syenite less than a foot in diameter. This mine was abandoned because of the large number of these decomposition boulder remains.

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PLATE VI.

(6) The bauxite beds are found through a vertical range of over 200 feet in the Bauxite District alone, a fact which, together with the uniform nature and thickness of the deposits, can hardly be reconciled with the idea that the deposits are chemical sediments precipitated from solution in a shallow sea. (7) The high porosity of the bauxite is taken as evidence of its residual origin. The average porosity of bauxite is in the neighborhood of 40 per cent., and locally as much as 60 per cent., which is higher than would be expected in a sedimentary deposit either of chemical or fragmental origin. This porosity is in accord with the volume of material leached from the syenite in the formation of the bauxite. (8) The bauxite and associated clays contain certain accessory minerals native to the syenite which have remained unaltered during the decomposition of the parent rock. These minerals which have been previously described are found evenly distributed through the bauxite in a manner not possible were the bauxite of sedimentary origin. In the detrital bauxite they are found more or less segregated into bands and bunches as is to be expected since the minerals are all of high specific gravity as compared with the bauxite and would tend to be concentrated by the action of water. That the bauxite found interstratified with the Tertiary sediments originated on the syenite surface is evidenced by the fact that abundant samples from drill holes yielded the same group of heavy accessory minerals as did the bauxite occurring in place on the syenite. No exposures of transported bauxite were examined and the manner of occurrence of these heavy accessory minerals is not known. (9) Chemical analyses of samples show a complete and uniform gradation in composition between the unaltered syenite through the kaolinized phase to the bauxite. There is no sharp break at any point in the gradation. The gradation from syenite to kaolin is shown by numerous analyses to be of a normal type of surface weathering. In the following table are analyses of samples from the same locality. No. 1 is fresh syenite from the cut near the Lantz Mine. No. 2 is partially kaolinized syenite. No. 3 is completely kaolinized syenite containing some bauxite, and No. 4 is bauxite.

TABLE I.

ANALYSES OF A SERIES OF SAMPLES FROM THE SAME LOCALITY SHOWING GRADATION FROM UNALTERED SYENITE NO. 1 TO BAUXITE ORE NO. 4.

	No. 1.	No. 2.	No. 3.	No. 4.
SiO_2	58.00	52.64	39.80	10.64
Al_2O_3	27.10	29.56	37.74	57.48
Fe_2O_3	1.86	1.06	1.60	2.56
FeO	3.30	.80	.10	.20
MgO	.25	.00	.00	——
CaO	1.62	.00	.00	——
Na_2O	6.70	4.46	——	——
K_2O	.25	.44	——	——
TiO_2	.40	1.20	3.30	1.20
H_2O	1.22	9.00	17.00	28.36

In Fig. 6, the volume compositions of the four samples are shown in terms of minerals and pore space. The porosity in each case was actually determined and the relative amounts of minerals calculated from the above analyses. The gradation is ob-

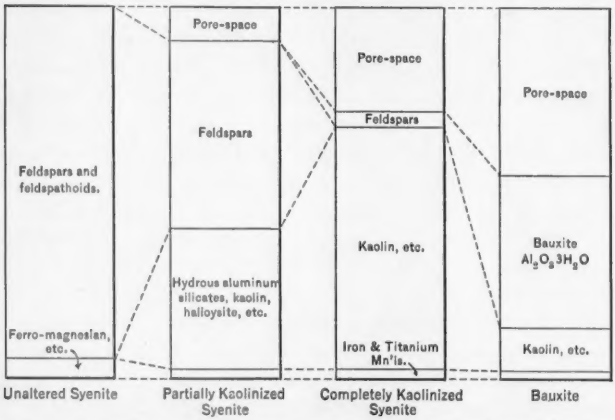


FIG. 6. Diagram showing in terms of volume, the mineral gradation from syenite to bauxite. The columns represent a series of samples from a single locality.

vious. In the triangular diagram, Fig. 7, a number of analyses of syenite, kaolinized syenite, clay, and bauxite have been platted

on the basis of chemical composition. Each of the small triangles represents a single analysis and by its position in the large triangle indicates the percentage of Al_2O_3, H_2O, and SiO_2.

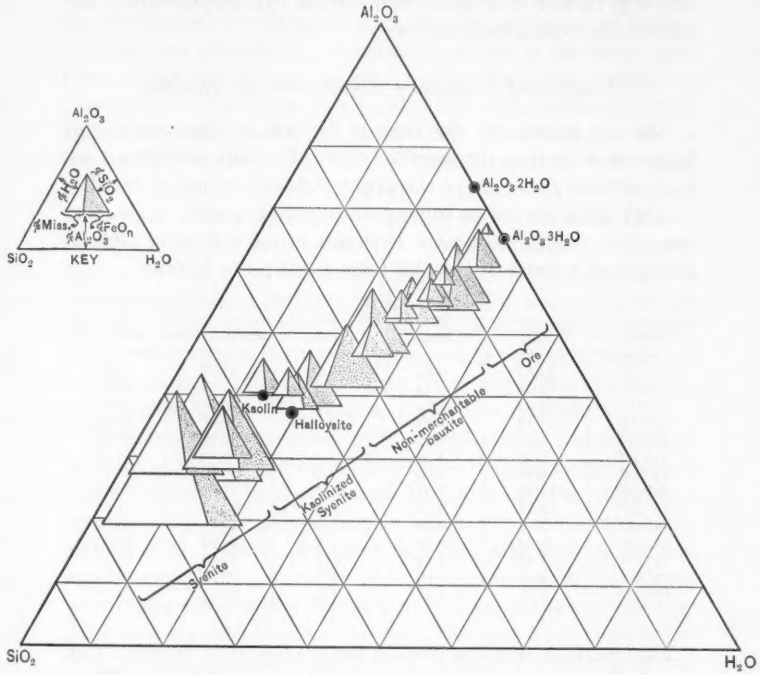


FIG. 7. Triangular diagram showing the gradation from syenite to bauxite in terms of the principal chemical constituents. Each triangle represents an analyzed sample.

The distance up from the base of the large triangle indicates the percentage of Al_2O_3, the distance from the left side of the large triangle shows the percentage of H_2O and from the right side the percentage of SiO_2. The amount of Fe_2O_3 in each analysis is shown by the shaded area and may be read at the base of the small triangle. The gradation from the syenite through the

kaolinized phase to the low grade bauxite and to merchantable ore is well shown here. It appears that normal weathering of the syenite to kaolin and allied minerals has simply continued one step further in breaking down these hydrous aluminum silicates to hydrous aluminum oxide.

Downward Secondary Enrichment of Alumina.

The top portion of the bauxite deposits is characteristically higher in silica than the bauxite below. In many instances it has been necessary to remove the upper eighteen inches or two feet of high silica ore before mining, thus adding greatly to the mining cost. A typical instance is shown in the following table of analyses of a series of samples from a test pit in bauxite.

Marked.	SiO_2.	Fe_2O_3.	TiO_2.	Loss on Ignition.	Al_2O_3 by Diff.
3′–5′	24.85	4.84	1.3	22.97	46.04
5′–8′	13.54	3.14	1.5	27.52	54.30
7′–9′	14.63	3.24	1.5	28.22	52.41
9′–11′	7.73	2.63	1.3	30.36	57.98
11′–13′	9.96	3.19	1.4	29.04	56.41
13′–15′	9.65	1.59	1.7	29.89	57.16
15′–17′	9.00	2.99	1.6	29.56	56.76
17′–19′	13.29	2.32	1.8	27.69	54.90
19′–21′	11.88	2.11	1.8	28.44	55.77
21′–23′	7.08	2.57	2.0	30.25	58.09
23′–25′	6.84	2.02	1.7	29.91	59.53
25′–27′	7.33	3.04	1.7	30.63	57.30
27′–29′	5.52	2.16	2.8	30.69	58.83
29′–31′	5.70	2.11	1.9	30.53	59.76

This increase in silica toward the surface may be due to an actual downward secondary concentration of alumina. Those portions of kaolin and halloysite which persist after the main portion of the kaolinized syenite has been altered to bauxite are the dense impervious parts. Bauxite is soluble in surface solution to a certain extent and on being dissolved and carried downward leaves the kaolin and hence the silica in relatively higher percentage at the surface. The alumina carried down is deposited below, assisting in the formation of the pisolites.

Open Texture Essential to Change from Kaolin to Bauxite.

The clay masses associated with the bauxite are of two types. One is a porous cellular phase preserving perfectly the texture of the syenite and consisting of a sponge-like aggregate of kaolinized feldspar individuals. It generally occurs in the lower portions of the deposits and is locally called kaolinized syenite or "underlay." This type is a transitional stage between syenite and bauxite and grades into both. The open texture is due to the openings left by the decomposition and removal of the easily altered mineral nepheline. The other type of clay is of a dense impervious nature frequently occurring in large masses extending to the surface of the bauxite. Abundant slickensided partings occur and color bands marking former joint planes or the transient outlines of boulders of decomposition are contorted and faulted. These facts are taken as evidence of slumping or packing of the kaolinized rock. There is no evidence whatever to indicate that the parent rock of the dense clay differed from the type of rock from which the porous clay was derived.

The occurrence of masses of unaltered clay at the surface of the bauxite raises the question as to why the clay escaped alteration to bauxite. An obvious explanation is that the impervious texture of the clay prevented circulation of solutions and made alteration to bauxite impossible and that alteration to bauxite has proceeded only in those portions of the kaolinized syenite which have escaped this slumping or packing process. This suggests that the alteration of the nepheline syenite to bauxite has been possible because of the porous or spongy texture imparted to the kaolinized rock by the removal of the mineral nepheline.

The alteration of clay to bauxite like other phases of rock decomposition is accomplished through the agency of circulating solutions. It, therefore, seems reasonable to assume that the rate of alteration is dependent at least in part on the permeability of the clay. This suggests that the characteristic stability of clay in general under surface conditions may be due to its equally characteristic imperviousness and that only open textured clays may be altered to bauxite.

The formation of aluminum hydrates as residual products of rock weathering has been frequently observed and described. A summary of the literature on this type of alteration is given by Clarke[4] in the "Data of Geochemistry." The formation of bauxite as a residual product of weathering has been observed for the most part in tropical and subtropical regions. It has been variously ascribed to the more active and complete leaching under tropical conditions of temperature and vegetation, to the action of bacilli or other microörganisms peculiar to the tropics, and to nitric acid produced by tropical thunderstorms. Lateritization has been so generally correlated with tropical conditions that it seems quite probable that the Arkansas bauxite was developed under a tropical or subtropical climate.

The reason for the confinement of lateritization to tropical or subtropical regions has long been an open question. If, as has been suggested above, an open texture in clay or kaolinized rock is essential to the development of bauxite, the question arises as to why open-textured clays should be peculiar to the tropics. A possible explanation of this may lie in the fact that the disintegrating action of frost on an open-textured clay would be to destroy the cellular structure and allow the clay to slump and become impervious. This would tend to retard further alteration of clays in regions subject to frost and to confine lateritization to the regions of little or no frost.

Origin of the Pisolitic or Oölitic Structure.

This peculiar structure which appears to be common to bauxite the world over, has been adequately described by Branner[5] and Hayes[6] for the Arkansas deposits. The oölitic type of ore consists of an aggregation of pisolites or oölites varying in size from microscopic to a maximum of an inch or in exceptional cases possibly more in diameter in a matrix of bauxite. The pisolites frequently, but not always, have a concentric structure marked by a variation of color bands, the coloring being due

[4] Bulletin U. S. Geol. Survey, No. 491, p. 469.
[5] *Op. cit.*
[6] *Op. cit.*

to ferric oxide. Occasionally oölites are observed to have a radiating system of cracks crossing the concentric banding. These cracks are usually cemented or filled by microcrystalline gibbsite. Dr. Branner, in one of his earlier reports, apparently observed this, but described it as quartz, the two minerals being very easily confused under the microscope. Some of the pisolites are compound, being made up of an aggregate of smaller individuals. Some of the pisolites or oölites are hollow at the centers and many of them have an extremely porous or spongy center within a comparatively thin shell of gibbsite. Many of the oölites on being broken open exhibit the texture of granitic ore, the feldspar shapes being very well and plainly preserved.

This peculiar pisolitic or oölitic texture, because of the fact that oölites have been thought to be the result of precipitation from solution in agitated waters, has in part led to the belief that the bauxite deposits themselves have originated in this manner. The oölitic texture of the bauxite has evidently led Dr. Hayes to believe that the ores have been precipitated from hot solutions, and consequently that the granitic type of ore represents replacement from hot solutions. As a result of a careful study of the oölitic ore and its relation to the granitic type of bauxite, the writer believes that this type of ore has been developed in place from the granitic or amorphous ore by the action of percolating water of the ordinary surface water type. The development of the pisolites is believed to be by a process similar to the formation of concretions. Conclusions are based on the following facts of observation. (1) Complete gradation may be observed between the granitic type of bauxite and the oölitic type, the oölites appearing in the granitic bauxite and becoming more numerous until the granitic texture is entirely obliterated. (2) The gradation from a textureless porous kaolin to oölitic bauxite can be observed,—the oölites beginning in very small individuals and becoming larger and more numerous as the ore is approached. (3) The relative position of the granitic and oölitic type of ore, the latter usually above the former where the surface solutions have been more active. (4) Microscopic examinations of the oölitic ore reveals abundant feldspar forms in the oölites (see

Plate V). These feldspar forms usually consist entirely of microcrystalline gibbsite, and are very striking indeed under the microscope, some of them even showing traces of the twinning of the plagioclase feldspars. (5) The solution and re-deposition of the bauxite is possible chemically as this material is soluble in acid solution. (6) This texture is common to bauxite deposits the world over and is taken as one of the principal means of identification of bauxite. This makes it probable that the texture is due to some common and widely prevalent set of conditions and processes. (7) A pisolitic structure very similar to that of the bauxite has developed under similar conditions in certain iron ores of eastern Cuba, known to be the residual products of weathering in situ of serpentine rock. (8) The presence of heavy accessory minerals common to the syenite, evenly distributed throughout the pisolitic type of bauxite is perhaps the most convincing evidence that this type of ore has developed from the syenite in place.

SOME OBSERVATIONS ON CONTACT METAMORPHIC ORE DEPOSITS.[1]

BASIL PRESCOTT.

A science such as the study of ore deposits shows, when broadly taken, what we like to consider as a steady and uniform progress towards the truth. The literature of such a science, however, shows that the advance is far from being uniform but consists rather of periods devoted to theoretical exposition and résumé, interspersed with periods' when, presumably, data are being gathered, and during which occasional contributions, largely of a descriptive nature, are presented. It might seem that the progress would result from the periods of careful study and limited exposition but, while accurate records and descriptions are absolutely essential to the development of a science, it is probable that the stimulative effect of the discussion following a generalized speculation is of scarcely less ultimate benefit.

Recently those interested in the type of ore deposits commonly described as contact metamorphic,—occurring usually at the contact between an igneous rock and a limestone and characterized by the development of a gangue of calcium-iron-aluminum silicates accompanied by both primary oxides and sulphides,—have been treated to a most interesting and instructive discussion of the subject by several of the exponents of the various diverging theories of their formation.[2] While the interest raised by such contributions is still intense, the following brief record and inter-

[1] Published with the permission of the American Smelting and Refining Co.

[2] J. F. Kemp, ECON. GEOL., Vol. 8, No. 6; W. Lindgren, *Trans. A. M. I. E.*, June, 1914, also ECON. GEOL., Vol. 9, No. 3; C. K. Leith, *Trans. A. I. M. E.*, June, 1914, also ECON. GEOL., Vol. 9, No. 3; W. L. Uglow, ECON. GEOL., Vol. 8, No. 1 and No. 3; C. A. Stewart, Vol. 8, No. 5, ECON. GEOL.; A. C. Lawson, *Min. and Sci. Press*, Feb. 3, 1912; J. B. Umpleby, ECON. GEOL., Vol. 9, No. 4; D. F. Higgins, ECON. GEOL., Vol. 9, No. 1.

pretation of observations in the field treated in the light of recent literature may perhaps be acceptable.

Lindgren[3] has reviewed the subject and has clearly and fairly stated the ideas held by each school. Briefly the three divergent views are as follows: 1st, the silicates and the metals are the result of circulating waters of meteoric origin heated by the intrusive and ascending along the contact. 2d, the silicates are principally the result of the recrystallization of the limestone carrying impurities though part of the silicates and all the metallic oxides and sulphides may represent additions from the igneous rock. 3d, the silicates as well as the metallic oxides and sulphides are due principally to additions from the igneous rock. Formation of silicates by recrystallization takes place only in proportion to the original tenor of the limestone in the required constituents and is considered often negligible and sometimes lacking.

In the early discussions of the relative merits of the latter two ideas as to the comparative importance of recrystallization, the subject was approached almost entirely from the standpoint of a comparison of the analyses of fresh limestone with the resulting silicate on the basis of equal volume. Kemp[4] and others showed by mathematical calculation that the limestone was often too pure to have furnished the material found in the silicate zone. In 1908, the writer described a deposit which occurred at the contact of a quartz diorite and an exceptionally pure limestone, and showed that for the principal silicate minerals the silica available in the limestone is less than 3 per cent. of the amount required in the most favorable case and the iron available is less than 1 per cent.[5] Such calculations together with the field observations of many competent geologists have not daunted the advocates of the recrystallization theory who point out that in some cases a concentration of the insoluble portions or residual constituents of the limestone would result in a mass approximating the chemical composition of the silicates of the contact zone. As the limestones are sometimes very pure (the combined silica,

[3] *Loc. cit.*
[4] J. F. Kemp and C. G. Gunther, *Trans. A. I. M. E.*, Vol. 38, 1907.
[5] ECON. GEOL., Vol. 3, No. 6, 1908.

alumina, iron oxides and magnesia often as little as from 3 per cent. to 10 per cent.) and the silicate zones relatively free from calcite, this conception necessitates an enormous shrinkage, the presence or absence of which appears now to be the critical point in the discussion. Microscopic examination in many cases shows the absence of the crushing and distortion that attends such shrinkage, but the supporters of the theory of recrystallization point out that later processes may have obscured the original evidence. Chemical and microscopical data having failed to yield unanswerable arguments the problem must now be attacked from the standpoint of broader structural relations to ascertain, if possible, if such shrinkage as postulated has taken place.

While these more basic considerations have not yet been settled to the complete satisfaction of the contending parties, other minor points of difference have arisen among those who accept the theory of the magmatic origin of the silicates and ores. These points are 1st, the order of deposition of the minerals, whether simultaneously deposited or in stages, and particularly whether or not the sulphides follow the silicates. As those who emphasize the stages in the deposition most strongly seem to believe that the whole is but a single progression, and that the stages often overlap, the differences of opinion on this point are probably not greater than the actual differences in the various occurrences; 2d, the condition of the intrusive at the time of the deposition of the mineral, particularly as to whether solidified or molten. 3d, the source of the mineralization whether in adjacent intrusive rock, whether in the heart of the intrusive rock on the same approximate horizon by mineralization along fractures through a solidified exterior, or whether from greater depths, presumably from deeper parts of the zone of differentiation.

The mineral sequence as well as many of the more intricate points in the history of the deposition must be determined by long and careful microscopic study of many deposits, a type of examination which unfortunately is not often undertaken. The condition of the intrusive, and some data on the source of the mineralization can often be determined from field relations, and

it is with these two and the reduction in volume required by the recrystallization hypothesis that this paper deals.

The pure lower Cretaceous limestone of Central Mexico with its great vertical range and its unvarying character presents in many respects better opportunities for the study of its ore deposits than do the sedimentaries of our own west and southwest with their mass of interbedded shales, limestones and quartzites. Variations attributed in other localities to changes in the wall rock must in the Cretaceous limestone of Mexico be explained on the ground of a variation in the mineralizer or in the physical conditions, as the only marked irregularity in the composition of the limestone is in its uppermost horizon where a transition into the overlying shale takes place.

At Santa Eulalia, Chihuahua, Mexico, there are two main types of ore, the earlier of which, a solid mass of small porosity, is marked by a silicate gangue containing ilvaite, a basic calcium-iron silicate practically confined to a contact deposits; fayalite, the iron olivine always reported heretofore in igneous rocks, though sometimes under conditions that suggest pneumatolitic origin; Knebeelite,—the iron-manganese olivine of the Swedish iron ore contact deposits; chlorite, an aluminum-iron-magnesium silicate, apparently here both primary and secondary,[6] and magnetite, often reported in contacts. The accompanying sulphides are generally pyrrhotite carrying silver and arsenopyrite carrying a trace of gold. The ore contains insignificant amounts of calcite, fluorite and quartz, but the above mentioned silicates are present in enormous quantities aggregating thousands of tons. No igneous rock aside from the small dikes unaccompanied by metamorphism are known in the district, although silicate bearing ores are exposed for nearly a thousand feet, and the limestone has been prospected to much greater depth. These silicates answer the requirements given by the supporters of the recrystallization hypothesis for minerals so formed, for they do not contain boron, fluorine, chlorine, beryilium, etc., and they are not metallic oxides or sulphides. The limestone around the silicate body has been

[6] A. F. Rogers, ECON. GEOL., Vol. 9, No. 4, p. 385, gives chlorite as a late magmatic or pneumatolitic mineral.

prospected, in at least two directions, for a thousand feet or more, and except for alteration by sulphate waters from the oxidizing ore bodies above it is a nearly pure calcium carbonate[7] lying almost horizontally bedded. The fact that the silicates do not occur in juxtaposition with the igneous rock does not vitiate the evidence afforded by them, especially as such occurrences have been quoted in support of the recrystallization hypothesis.[8]

Leith has recently made the following statement: "The reduction in volume required by the recrystallization hypothesis cannot in most cases be disproved."[9] Santa Eulalia must be added to the list of places where shrinkage can be definitely disproven since the silicates have there developed by the replacement of the limestone, the original bedding of which is often retained. Further there has been no local structural deformation of the limestone, the almost horizontally lying beds appearing in their normal position around the body of silicates. Aside from this direct evidence, it does not seem possible to conceive any combination of faulting, folding, or plastic deformation that would take up the reduction in volume required by the recrystallization hypothesis in such an enormous irregular mass of silicates included in a nearly pure limestone.

While the ore body has not yet been completely developed, it seems reasonably certain that the mineralizer, bearing silicates and ores, traveled vertically upward along definite fissures in the limestone, as borne out by the banding of their contents.

In the same district and a mile or two away from the above occurrence there is a slight silicate development which owes its origin to the concentration of the more insoluble constituents of a relatively pure limestone and probably to heat from some unknown distant source. In the fissures and breaks in the limestone underlying a large, open, "dry" (barren) solution cave of a

[7] Analyses are not available owing to present conditions in Mexico, but the limestone in Santa Eulalia is unusually uniform throughout and shows except in the immediate neighborhood of the ore body from 50 per cent. to 53 per cent. CaO. Smelter returns on flux from various horizons and different sections.

[8] C. K. Leith, *Trans. Am. Inst. Min. Eng.*, Vol. XLVIII., p. 211.

[9] C. K. Leith, *Trans. Am. Inst. Min. Eng.*, Vol. XLVIII., p. 211.

volume of from 50,000 to 100,000 cubic meters was found the usual accumulation of finely divided siliceous and aluminous material representing the insoluble constituents of the limestone of the cave. Parts of this accumulation have been metamorphosed in place to tremolite in the form of mountain leather. This I believe is the first indubitable occurrence reported of the development of silicates in accordance with the shrinkage idea of the recrystallization hypothesis, but in this case a comparison between the size of the cave and the silicate development serves but to emphasize the inadequacy of recrystallization as a considerable factor in the development of silicate bodies from a relatively pure limestone.

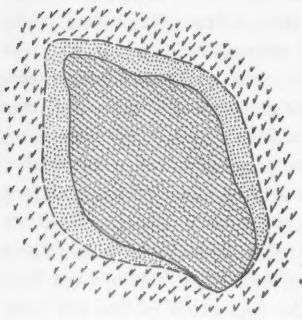
The Copper Queen occurrence at Velardeña, Durango, Mexico,[10] has been frequently cited in the literature of the subject. A little over a year ago, the writer examined a large number of diamond drill cores from various horizons of this mine as well as the workings and stopes. The mine now has a vertical depth of more than 1,500 feet measured from the outcrops of the main bodies. The developed monzonite is a relatively small, almost isolated mass, nearly surrounded by limestone though connected with a somewhat larger body. As is usually the case the silicates, largely garnet, do not form a band between the limestone and monzonite but are localized at points along the contact and in the mass of igneous rock. By far the greater part of the silicates are developed in the monzonite, and the texture or the minerals of the original rock can still be recognized, but a relatively small portion, —including some of the ore bodies,—is completely metamorphosed into a rock that can be referred on a structural basis only to igneous rock or limestone. A yet smaller portion appears definitely to be metamorphosed limestone. In plotting drill holes and mine workings, it was found that zones of metamorphosed monzonite, often 20 feet wide, extended across the mass from limestone to limestone not following the contact but independently of it, and that these continued vertically for several hundred feet joining and splitting and varying but continuous from the point where first recognized to the greatest depth

[10] J. E. Spurr and G. H. Garrey, Econ. Geol., Vol. 3, No. 8.

reached. The core of these bands may be completely metamorphosed into a silicate mass, but within a few feet on either side the gradation into the unaltered monzonite commences. Although definite fissures controlling these particular bands were not noted, the development of these garnet zones extending from limestone to limestone excludes the idea of the monzonite being molten at its center and cool at its periphery, and their vertical continuity seems to point towards a mineralizer travelling along them. Further, while in the upper horizon it was difficult to account for the location or shape of the ore body, with increasing depth the controlling factors became evident. Thus in Figs. 8, 9, 10, 11, the factor that controls the deposition of the ore body in the igneous rock was probably the irregularity of the limestone below, while the lengthening of the ore body on the upper horizon (Fig. 10) may be due to the proximity of the two limestones on the lower (Fig. 11). In each of these cases and in many others that arise constantly, the cause is found at some point below the effect, pointing to a reaction between an ascending mineralizer and the limestone, rather than between the monzonite and the limestone. The ore bodies are as a rule the centers of the principal masses of garnet rock though usually touching the limestone, and all important occurrences are chimneys or pipes which have a greater exposed vertical range than the diameter of the monzonite mass they accompany.

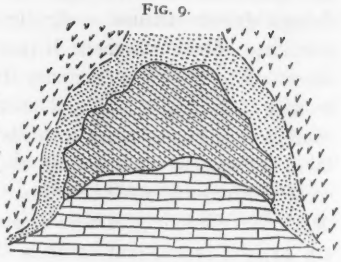
The Dolores and Cobriza occurrence at Matehuala, S.L.P., Mexico, is another often cited locality. Here metamorphism by recrystallization is found, but this is practically limited to certain upper horizons of the Cobriza mine where the transition from the limestone into the overlying shales takes place. In this transitional horizon the argillaceous beds have been metamorphosed by recrystallization for a considerable distance from the contact while the pure interbedded limestones are metamorphosed only near the contact. Throughout the 1,800 feet exposed in the workings at Dolores this type of metamorphism is noticeably lacking as are the impure limestones. This has been clearly

FIG. 8.



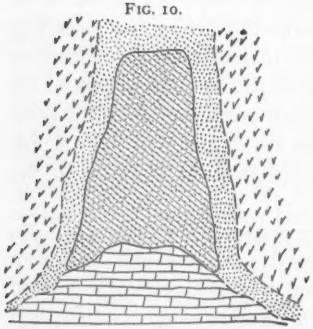
UPPER HORIZON

FIG. 9.



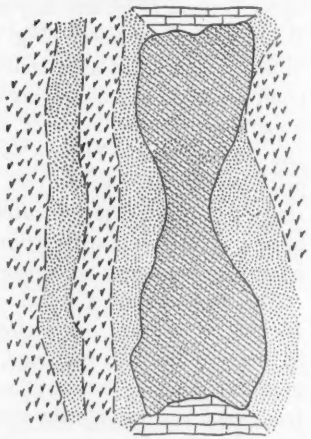
INTERMEDIATE HORIZON

FIG. 10.



LOWER HORIZON

FIG. 11.



DEEP HORIZON

Generalized Plans of Ore Chimney at Copper Queen Mine, Velardeña, Durango, Mexico.

stated by Spurr.[11] Similar metamorphism of argillaceous beds by recrystallization occurs at other Mexican localities usually only as an interesting phenomenon, for in the great mass of pure limestones recrystallization is ineffective as an agent of metamorphism. In a recent article in support of the recrystallization hypothesis, Uglow stated that "more attention would be given the nonmetalliferous portion than that which is composed chiefly of ore bodies."[12] If this were done, or better, if only occurrences were considered in which metallic sulphides in commercial quantities are lacking, recrystallization might be more often cited as a controlling factor, for it has been the writer's experience that as the development of silicates by recrystallization increases, the value of the contact metamorphic deposits from an economic standpoint rapidly decreases. As the interest of a considerable number of those following the development of the science is economic, it would seem that this point would bear emphasis.

At both Dolores and Cobriza the monzonite mass is not of great size, measuring a thousand feet or so in width and several times that length. The ore bodies are numerous and large, and occur both along the contact and around the limestone "islands" in the monzonite mass. Although irregular they are nearly vertical. The development of the silicates and ores is restricted to certain points, and there is not a continuous silicate zone between the igneous rock and the limestone. Marmorization recognizable to the naked eye is conspicuously lacking here as is often the case with the small monzonite intrusions of Mexico, and sometimes the contact for a considerable distance shows the unaltered blue limestone in contact with the unaltered monzonite.

Here as at Velardeña, there are many reasons for believing in the complete consolidation of the intrusion to the greatest known depths before the deposition of the silicates. It is not conceivable that either of these relatively small masses of igneous rock could be in a molten state in the center and at the same time cool enough along the peripherial zone for the formation of fractures

[11] J. E. Spurr, G. H. Garrey and Clarence N. Fenner. ECON. GEOL., Vol. 7, No. 5.

[12] ECON. GEOL., Vol. 8, No. 1.

and fissures, nor is there any evidence of a differentiation toward the center. At one place at Dolores where two limestone islands lie in the intrusive, the width of the unaltered monzonite is only about 300 or 400 feet, although the total width of the intrusion is nearly one thousand feet. Further, a strong quartz vein several feet wide cuts across the unaltered monzonite near the point of maximum width, and at its intersection with the north contact forms a silicate body largely of wollastonite. Fractures and even sheeting have been noted, all apparently with direct bearing on the ore and silicate deposition. Here, as at Velardeña, the ore and surrounding silicates in the form of pipes or chimneys are controlled by the features of the contact below, rather than by those of the horizon at which they happen to be exposed on the surface or in mine workings.

One of the most general characteristics of the contact metamorphic ore deposits is the development of the silicates and ores at concentrated points, the locus of which is a protrusion of the limestone into the igneous rock, or a mass of limestone included in it. The mineralogical development both in ores and gangue, the size or shape of the intrusion, the amount and the distance covered by metamorphism, the character of the limestone and even the viewpoint of the observer may all vary and result in widely varying descriptions of different localities, but in the majority of cases some mention is given or some inference may be drawn from text or illustrations, that the mineralization is more pronounced at the limestone points that protrude into the igneous rock than elsewhere. Even on the included blocks, the important silicate and sulphide developments are often confined to the points of the limestone to the exclusion of embayed areas or plain surfaces, and where this relation is not clear on the surface, it develops with depth. Although this has often been overlooked in discussions, any hypothesis for the genesis of contact metamorphic deposits must satisfy the conditions imposed by this type of occurrence, and it would almost seem that any hypothesis that explains the localization of the ore and silicate at known horizons, on these limestone protrusions surrounded at the time

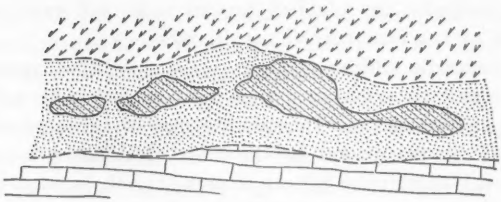


FIG. 12. UPPER HORIZON.

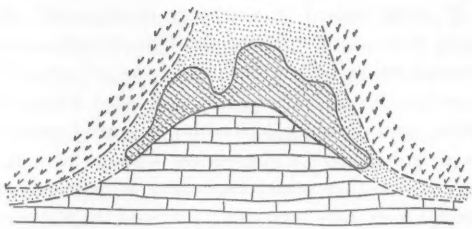


FIG. 13. INTERMEDIATE HORIZON.

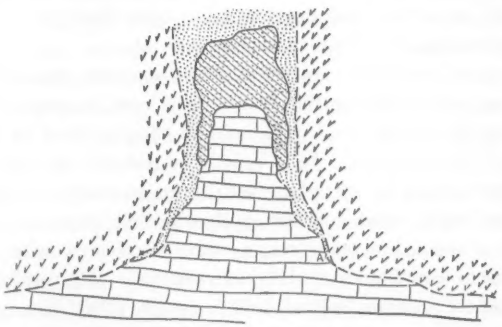


FIG. 14. DEEP HORIZON.

Generalized plans of Ore Chimney at Dolores Mine, Matahuela, San Louis Potosi, Mexico.

of their formation by solidified igneous rocks will explain the genesis of contact metamorphic ore deposits.

It is admittedly difficult to disprove the shrinkage hypothesis where the silicates occur as a zone between limestone and igneous rock no matter how strongly one may be led to believe in additions from the magma by the mass of evidence favoring them, but it is much more difficult to prove shrinkage when these chimney like bodies of silicates and ores, localized on a point of limestone, are given the importance that they warrant in many deposits. It would indeed be a strange development of structural features that would take up the loss in volume required by the recrystallization hypothesis in a body as in figure 14 standing nearly vertical for a thousand feet, and when a large number of such bodies, some of which join with depth, are found around a small mass of monzonite, the conception is untenable. It would require deformation that would feed solid limestone through a restricted neck (A–A′), as open space followed the elimination of lime, and the axis of the disturbance would stand vertical. It is hardly necessary to state that at the localities described, no evidence of structures thus developed has been found in the limestone points bearing these chimneys.

In many occurrences as described by eminent observers, the metamorphism found in the contact zone consists principally of the development of lime-iron-aluminum silicates in or at the expense of the limestone. It is usually considered that these silicates are formed by the addition of large amounts of iron, alumina and silica which together with whatever impurity may be present in the sedimentary reacts with the calcium oxide of the limestone to form lime-iron-aluminum silicates. The resulting silicates however contain only a portion, usually a half to a quarter, of the lime of the original rock and the elimination of the excess of calcium oxide with the carbon dioxide is usually considered as a necessary step in the formation of such deposits. These conditions are certainly not general, for at Velardeña the replaced limestone at known horizons is not sufficient to supply the lime

required by the mass of calcium-iron-aluminum silicates in the monzonite, and it seems probable that the same is true in many instances at Dolores, though owing to the greater size of the intrusion it is more difficut to make an estimate. It would seem that the occurrence of the large bands of calcium silicates extending across the monzonite at Velardeña, the occurrence of an ore body surrounded by metamorphic minerals largely derived from replacement of the monzonite, above a point of limestone, and the occurrence of large masses of silicates in the monzonite next to unaltered limestone which appears to present its original contact to the metamorphosed monzonite,—would all point towards one conclusion, that in many cases the mineralizer is sufficiently saturated with lime at the point of deposition to form calcium silicate without local additions from the limestone. It does not necessarily follow that the magma provided this lime, nor is it asserted that the limestone at known horizons did not supply a considerable part of the required calcium oxide, but rather that the principal zone of reaction between the limestone and the igneous emanations was not necessarily the principal zone of deposition. Further the iron-alumina silica addition from the magma in some cases replaces the limestone without reaction with the displaced calcium carbonate, for at Santa Eulalia a limestone containing approximately 50 per cent. calcium oxide is replaced by a mass of silicates and ore containing approximately 5 per cent. calcium oxide.

Both types of metamorphism take place at known horizons; that is metamorphism by reaction between mineralizer and limestone where part of the lime enters into the composition of the resulting silicates; and metamorphism by replacement of either igneous rock or limestone. Any distinction must be based on the ground of a comparison of the ratios between the two processes. It is also probable that metamorphism of the *limestone* by replacement without reaction is a relatively rare occurrence, limited to deposition under conditions of low temperature and to zones above those at which reaction is possible. From Koenigs-

berger's[18] results it would seem that the formation of the common lime bearing silicates can take place through a considerable range of temperature, but that the higher temperatures are more favorable for their formation. Disassociation of the calcium carbonate is not necessary, for the excess of lime resulting from the replacement of an area of limestone by the silicate minerals may furnish the required calcium oxide for the higher horizon, at which point the reaction between the mineralizer now carrying both the additions from the magma and the calcium carbonate may take place.

Among the many factors that probably control the ratio of lime set free to that deposited in silicate, the most important are, perhaps, the extent and purity of the limestone below the zone observed, the position of the more or less accidental and very restricted zone of observation in the total range of deposition, and the size and temperature of the intrusion, particularly the amount of chilling that has taken place during this intrusion.

These considerations would seem to point towards certain limiting conditions which any hypothesis for the genesis of these deposits must satisfy. They are not given as a complete list of requirements for all deposits on all horizons, but rather as those prominent in several localities studied by the writer and hence those which among others must be satisfied in any general hypothesis.

1. At least to the greatest depth reached, the intrusion is often a solidified mass capable of fracture at the time of the formation of the contact silicates.

2. The ore bodies are localized on points of limestone protruding into the igneous rock both when these protrusions are portions of the main mass of limestone and when they are portions of included limestone "islands."

3. Where the igneous rock has embayed the limestone, megascopic development of metamorphism is almost invariably absent.

4. Marmorization of the limestone is often absent even when the neighboring monzonite shows heavy development of silicates.

[18] J. Koenigsberger, ECON. GEOL., Vol. 7, No. 7.

5. There are horizons at which the replaced limestone does not furnish sufficient lime to account for that found in the silicates as there are also horizons at which the lime of the replaced limestone is in excess of the requirements.

6. There are horizons at which iron-aluminum silicates replace the limestone without reacting with it to form lime-iron-aluminum silicates.

7. The mineralizer appears to have been ascending and to have come from below the greatest depth yet reached.

ALUNITE AND PYROPHYLLITE IN TRIASSIC AND JURASSIC VOLCANICS AT KYUQUOT SOUND, BRITISH COLUMBIA.[1]

CHARLES H. CLAPP.

INTRODUCTION.

A few years ago Ransome[2] stated, in opposition to the explanation of alunitization by the "direct volcanic" hypothesis, that "if sulphuric acid were formed in any considerable quantity at great depth during volcanic activity we should expect to find alunite a more common constituent of rocks which have been uncovered by erosion than experience indicates." Since then alunite has been found in the United States at several places[3] not known at the time and is recognized as a more common alteration product of feldspathic igneous rocks than it was formerly supposed to be. In previously described deposits[4] the alunitized rocks, chiefly feldspathic volcanics, are Tertiary or younger and have not been deeply eroded; or else the alunitized rocks, not only volcanics, but porphyries and Paleozoic limestones,[5] have been intruded by young, usually Tertiary, volcanics and have not been eroded greatly since alunitization. However

[1] Published by permission of the Director of the Geological Survey of Canada.

[2] "Geology and Ore Deposits of Goldfield, Nevada." Prof. Paper, No. 66, 1909, p. 191. Mr. Ransome of course recognized that in some cases of alunitization the "direct volcanic" hypothesis was apparently the most satisfactory.

[3] Butler, B. S., and Gale, H. S., "Alunite, a Newly Discovered Deposit near Marysvale, Utah." Bull. U. S. Geol. Survey, No. 511, 1912. Larsen, E. S., "Alunite in the San Cristobal Quadrangle, Colo.," Bull. U. S. Geol. Survey, No. 530–F, 1912. Schrader, F. C., "Alunite in Arizona and Nevada," Bull. U. S. Geol. Survey, No. 540–I, 1913.

[4] See Butler, B. S., and Gale, H. S., *op. cit.*, pp. 38–58, for excellent and concise summary of alunite deposits known in 1912.

[5] Schrader, F. C., "Alunite in Granite Porphyry near Patagonia, Arizona, and Alunite at Bovard, Nevada." Bull. U. S. Geol. Survey, No. 540–I, 1913

at Kyuquot Sound, Vancouver island, there are alunitized and pyrophyllitized volcanics of Triassic and Jurassic age, that have suffered a great deal of erosion, 4,500 feet at the least, and probably very much more. Neither are these old volcanics cut by young volcanic rocks, none of which, in fact, are known on Vancouver island. Thus, since there is no probability of the alunitization or pyrophyllitization having been caused largely by descending meteoric solutions during the present erosion cycle, it appears that here is an instance where alunite rocks have been uncovered by deep erosion.

These deposits of alunite and pyrophyllite are the only ones of their kind known in Canada or indeed in the entire northwestern part of North America. Although previously known, they were first located in 1908 by Dr. F. W. Morris, of Victoria, and since then the pyrophyllite rock, and to some extent the alunite rock, has been utilized by the British Columbia Pottery Company as a fireclay and by the San Juan Mining and Manufacturing company as a powdered cleanser. Of late years alunite has attracted considerable attention as a possible source of "potash" as well as of alum, and it has even been suggested as a possible source of aluminum oxide.[6] In view of this the writer was directed to make an examination of the deposits for the geological Survey of Canada, and accordingly he spent four days during July, 1913, in examining them.

LOCATION AND TOPOGRAPHY.

The principal alunite and pyrophyllite deposits are situated on a small peninsula in the northwestern part of Kyuquot sound, between Kokshittle arm and a small inlet called Easy Creek. Kyuquot sound is one of the six large fiords which indent the west coast of Vancouver island and afford access into the heart of the Vancouver range. It is situated in the northern part of the island, between Esperanza inlet and the northernmost fiord, Quatsino sound. Kokshittle arm is the most northwestern of the several straight, narrow, deep arms which lead into the open

[6] Butler, B. S., and Gale, H. S., *op. cit.*, pp. 58–61.

islanded portion of Kyuquot sound; and entering the outer portion of Kokshittle arm from the west, is Easy Creek.

The elevation of the plateau portion of the Vancouver range, formed by the uplift of an old erosion surface of subdued outlines, varies in the vicinity of Kyuquot sound from about 2,500 feet near the ocean, to about 3,500 feet near the inner portion of the sound. Surmounting the general plateau surface are numerous rounded summits that attain elevations of 4,000 to 4,500 feet. In the immediate vicinity of the sound the plateau has been destroyed and reduced to a large number of diversely arranged hills and ridges of unequal height. The four or five rounded hills and ridges which compose the small peninsula, about two miles long and 1,500 to 3,000 feet wide, trending northwest between Kokshittle arm and Easy Creek, are only from 250 to 500 feet in height and are arranged along the axis of the peninsula in such a manner that the northeast slope to Kokshittle arm is somewhat gentler than the slope to Easy Creek.

GENERAL GEOLOGY.

The rocks in the vicinity of the alunite and pyrophyllite deposits are chiefly the Vancouver volcanics of Triassic and lower Jurassic age.[7] They consist of a series of interbedded amygdaloidal, porphyritic, and fragmental feldspathic andesites and dacites, at least 10,000 feet thick, which although involved in several minor folds, have a general east-west strike and southerly dip of 20 to 40 degrees. They are broken by small normal faults and by rather numerous shear zones, which are larger and more numerous near and in various rocks derived by the alteration of the volcanics. The volcanics have been intruded by a feldspathic quartz diorite, exposed only in the northern part of the region, and considered to be of upper Jurassic age since it appears to be the peripheral phase of a large granodiorite batholith of the Coast Range or Saanich type.[8] The volcanics are

[7] See Clapp, C. H., "Southern Vancouver Island," Memoir No. 13, Geol. Survey, Canada, 1912; pp. 68–71.

[8] *Op. cit.*, pp. 112–113.

cut also by a few dikes of quartz, bearing diorite porphyry, apparently an apophysial phase of the quartz diorite, and by numerous dikes of andesite porphyry. Similar andesite porphyry dikes cut the feldspathic quartz diorite, but many of the andesite porphyry dikes are so similar in character to the volcanics and are so closely associated with them, occurring seven miles from the feldspathic quartz diorite, that many, if not most, are best correlated with the volcanics and considered injected equivalents of them. In places near the intrusive feldspathic quartz diorite, the volcanic rocks, especially the fragmental varieties, have been metasomatically replaced by quartz, sericite, chlorite, pyrophyllite, alunite, and diaspore, forming altered or metasomatic rocks of four principal types, which are called (1) quartz-sericite-chlorite rocks, (2) quartz-sericite rocks, (3) quartz-pyrophyllite rocks, and (4) quartz-alunite rocks.

CHARACTER AND OCCURRENCE OF THE ALTERED ROCKS.

The altered rocks are found at several places within two to three miles of the intrusive feldspathic quartz diorite, but with the exception of the least altered type, the quartz-sericite-chlorite rocks, are confined largely to the outer, northwestern portion of the small peninsula between Kokshittle arm and Easy Creek. On the peninsula the altered rocks are divided into two areas by a band of unaltered volcanics, 500 to 1,500 feet wide, which extends across the northwestern portion of the peninsula. The southern area is from 200 to nearly 1,000 feet wide. The northern area is rudely triangular and is over 2,000 feet long, measured along the northern shore of the peninsula, and 1,500 feet wide. Although closely associated with one another the different altered rocks form separate, well-defined, and fairly uniform masses, which have been mapped separately.

Quartz-Sericite-Chlorite Rocks.

The quartz-sericite-chlorite rocks are the most abundant of the altered types. They occur surrounding the other altered rocks, forming wide transition zones between the comparatively unal-

tered volcanics and those most completely replaced. They also form a zone one fourth of a mile to one mile wide, in contact with the intrusive feldspathic quartz diorite, and thus appear to be partly the result of the contact metamorphism of the unaltered volcanics. They are chiefly dense, light to dark greenish rocks, which retain the porphyritic, amygdaloidal, or fragmental texture of the primary dacites and andesites. They consist largely of an irregular but extremely fine-grained (0.005 to 0.2 mm.) intergrowth of secondary minerals, chiefly sericite and chlorite, and almost invariably contain finely granular pyrite and chalcopyrite.

Quartz-Sericite Rocks.

The quartz-sericite rocks are dense and in places cherty, light bluish gray to flesh-colored, although stained with hydrous iron oxides on their weathered surfaces. Besides quartz and sericite, virtually the only other minerals present are pyrite, limonite, and kaolin.[9] The rocks are chiefly of fine, and irregular grain, varying from 0.001 to 0.01 mm., but pyrite occurs in small regular crystals which have apparently replaced the quartz and sericite, and hence appear to be of later formation.

Quartz-Pyrophyllite Rocks.

The quartz-pyrophyllite rocks are found on the Deertrail claim on the west side of the peninsula and on the Monteith claim on the east side, foming compact masses of three acres and one acre respectively, and the tonnage above sea-level is about 400,000 tons in the former deposit and about 100,000 tons in the latter. Since the deposits have apparently been formed by ascending solutions it is probable that they extend for an indefinite, but not very great distance below sea-level. Although fairly pure, they contain some quartz-sericite rocks, which of course cut down the available tonnage. These occur in the Deertrail claim deposit as irregular streaks, apparently following shear zones, and in the Monteith claim deposit so interbedded with the quartz-pyro-

[9] A partial chemical analysis and the mineral composition of a typical quartz-sericite rock is given in the table on page 15.

phyllite rocks that it appears as if some beds of the originally thin bedded and southerly dipping volcanics had been replaced by quartz and sericite and other beds by quartz and pyrophyllite.

The quartz-pyrophyllite rocks are all dense, usually having a pronounced greasy or soapy feeling and are easily crushed to a very fine, smooth powder, their use as a clay and powdered cleanser being dependent upon this property. Much of the rock contains disseminated small grains of pyrite or small masses of finely granular pyrite, and these pyritic varieties are invariably light gray to rather dark bluish gray in color. These rocks are not only stained yellowish or reddish brown on exposed surfaces, but pass into reddish, pinkish, or cream colored rocks, which have apparently been leached of pyrite. The minerals of the rocks are essentially quartz and pyrophyllite with accessory sericite and small amounts of pyrite, limonite, and kaolin. Since the analyses[10] show the presence of almost as much soda as potash, it is probable that the rocks contain a small amount of unreplaced or secondary feldspar. Some alunite is found in the quartz-pyrophyllite rocks, as some pyrophyllite is found in the quartz-alunite rocks, but for the greater part each rock is free from the characteristic component of the other. Most of the rocks show that they have resulted from the metasomatic replacement, chiefly of fragmental, but in some instances of porphyritic and amygdaloidal volcanics. They are very fine grained and some of the quartz is so fine grained that it is microaphanitic, that is, its crystalline character is doubtful; and it is possible that some of the secondary silica occurs in the form of opal.[11] The pyrite usually occurs in small euhedral grains, which have apparently replaced the metasomatic rock. The pinkish and cream colored rocks contain no pyrite, but contain a little limonite, and also a dense, white, opaque substance, presumably kaolin. This supposed kaolin occurs in small regularly shaped patches which are apparently pseudomorphs after pyrite, and in the grayish

[10] See chemical and mineral composition of two typical quartz-pyrophyllite rocks given in table on page 15.

[11] *Cf.* "Alunite Rocks in San Cristobal Quadrangle, Colo., Larsen, E. S.," Bull. U. S. Geol. Survey, No. 530-F, 1912, pp. 5-6.

rocks the kaolin and pyrite occur together in such a manner that the kaolin appears to be replacing the pyrite.

Quartz-Alunite Rocks.

The quartz-alunite rocks form, at the extreme northwestern point of the peninsula, on the Morris claim, a large mass of about 4½ acres in area, containing above sea-level about 600,000 tons, and another much smaller mass along the shore to the east, on the Snowstorm claim. It is believed that the alunite rocks, like the pyrophyllite rocks, extend below sea-level for an indefinite distance, which, however, is probably not more than a few hundred feet.

The alunite rocks are extremely fine grained, dense, and in places porcelain-like, possessing a hackly fracture and a harsh to a hard, finely gritty feel, and a few of them are foliated. They vary in color in much the same way as the quartz-pyrophyllite rocks, from a light to dark bluish gray through reddish and pinkish colors to cream and white. The bluish gray rocks almost invariably contain more or less pyrite, either as disseminated minute grains, or in small, very finely granular masses. The red, pink, cream-colored, and white rocks are almost free from pyrite, although with the exception of some white, porcelain-like varieties, all the rocks are stained red, yellow, or brown on their weathered surfaces with iron oxides. The grayish blue rock is found chiefly near sea-level, that is, near or below ground-water level, while above the ground-water level, the rock is chiefly of the pink or cream-colored variety, but these light-colored rocks frequently contain cores a few inches in thickness of the bluish gray rock. It thus appears that these reddish to pink and cream to white rocks have been formed during the present cycle by the partial to total leaching and oxidation of the pyrite by descending meteoric waters; and doubtless below the present ground-water level the grayish blue rock would predominate. The ability of these waters to leach the alunite rocks of iron is strikingly shown by the cementing with limonite of the beach detritus fringing the alunite deposit, a process still in vigorous action.

The alunite rocks consist essentially of quartz and alunite, which is the sodic alunite properly called natroalunite,[12] with accessory diaspore and sericite in places. Pyrite, as mentioned, is accessory in the bluish gray rocks. The only other minerals noted are kaolin, sulphur, and limonite, but these have probably been the result of recent surface alteration. Since the analyses[13] of the quartz-alunite rocks show more than sufficient alkalies to combine with alumina to form alunite and sericite, it is probable that some undecomposed or secondary feldspar occurs in the rocks. The large percentage of water suggests the presence of hydrargillite also, but neither of these minerals was detected microscopically. The quartz-alunite rocks are clearly seen to have resulted from the metasomatic replacement of fragmental and occasionally porphyritic volcanics. They are fine grained, the alunite varying from 0.005 to 0.3 mm. in diameter, and the quartz from 0.005 mm. to almost sub-microscopic in size. The diaspore occurs in well-defined, lath-shaped to acicular grains which are usually diversely arranged, but which in some rocks have either a subparallel or radial arrangement. As in the quartz-pyrophyllite rocks, pyrite occurs in small grains, many of which have regular crystal outlines and have apparently replaced the alunitized rock.

ECONOMIC DEVELOPMENT AND POSSIBILITIES.

Several claims have been taken up on the pyritized and altered rocks, which have been considered to be of value for gold and copper, for alunite or alum, and for pyrophyllite, but even the most highly mineralized deposits, the metallic minerals consisting almost entirely of chalcopyrite and pyrite, are too small and too low grade to be considered as possible sources of copper ore. Neither are the gold and silver values, ranging from $0.30 to $1.10 in gold and about 20 cents in silver, sufficient to encourage any considerable development.

[12] Hillebrand, W. F., and Penfield, S. L., "Some Additions to the Alunite-Jarosite Group of Minerals," in Bull. U. S. Geol. Survey, No. 262, 1905, pp. 37–41.

[13] See chemical and mineral composition of two typical rocks in the table on page 15.

As yet the San Juan Mining and Manufacturing Co., who own the alunite deposits, have not used the alunite rock although they have announced their intention of manufacturing alum. Alunite is at present considered to be of value not only for alum, which is now extracted from it, but also as a source of "potash salts" for fertilizers, and as a possible source of aluminum ore. Since the Kyuquot deposits contain a large percentage of impurities, and since the alunite is of the sodic variety, they are not very promising as a source of alum or other potash salts. It is, however, to be hoped, considering the large quantities of alunite available, that some use for it may be found.

The quartz-pyrophyllite rock has been used successfully by the British Columbia Pottery Co. as a "fire-clay" to mix with surface clays and Cretaceous shales to increase the refractiveness of the mixture, which is used to manufacture sewer-pipe and fireproofing. It has also been used by the San Juan Mining and Manufacturing Co., who have taken advantage of the extremely fine grained character and slipperiness of the rock to manufacture a powdered "household cleanser," a metal polish, and a mechanic's soap. If the coarser grains of quartz are perfectly eliminated it is understood that the products are of good grade. It is probable that the pyrophyllite rock might be employed as a substitute for powdered massive talc for other uses; and an increasing use for the material may be found. Although the deposits are not large, they are doubtless large enough to meet any demand that is likely to be put upon them for a great many years.

ALTERATION OF THE VOLCANICS.

Since the original textures of the volcanics are preserved in the various altered rocks, it is clear that the Kyuquot sound alunite and pyrophyllite deposits have been formed by the metasomatic replacement of the Vancouver volcanics, chiefly the fragmental varieties. As the altered rock masses show no evidence that either swelling or contraction took place during the replacement of the volcanics, it is supposed that the replacement took place without change in the total bulk of the original vol-

canics.[14] However, the altered rocks are slightly more porous than the volcanics, indicating that a slight reduction in volume took place.[14] As shown by a comparison of the specific gravities and porosities of the altered rocks with the specific gravity and porosity of the original fragmental dacite indicated in the following table, the increase in the porosity of the altered rocks is not sufficient to offset the increase in density; so that in all cases the fragmental dacite has not only gained slightly in weight, from 1.9 to 7.8 per cent., but, even considering equal volumes of the naturally porous, fresh and altered rocks, there has been a slight addition of material, from 0.4 to 7.5 per cent.

The chemical and mineralogical changes undergone during the metasomatism of the fragmental dacite, resulting in the quartz-sericite, quartz-pyrophyllite, and quartz-alunite rocks, are shown by the accompanying table and straight-line diagram, Fig. — invented and described by W. J. Mead.[15] No chemical analyses of the quartz-sericite-alunite rocks were made, as it does not seem as if the chemical change resulting in them is very marked. The diagram is simply a graphic method of representing the changes, by plotting the quotients, multiplied by 100, obtained by dividing the per cent. of each constituent in the fresh rock by the per cent. of the same constituent in the altered rock. The slope of the lines on the diagram indicates at a glance the relative behavior of the several oxides during the production of the three types of altered rocks from the same original rock. As described above, a comparison of the densities and porosities of the fresh and altered rocks indicates that there has been a slight gain in substance during the alteration; that is, considering the porous rocks, 100 grams of fresh rock has resulted in 100.4 to 107.5 grams of altered rock. Thus as the quotients plotted in the diagram represent for each constituent the number of grams of altered rock required to contain the amount of that con-

[14] *Cf.* "Alunite Rock Formed by Replacement of Dacite"; Ransome, F. L., "Geology and Ore Deposits of Goldfield, Nevada," Prof. Paper, U. S. Geol. Survey, No. 66, 1909, p. 180.

[15] Mead, W. J., "Some Geologic Short Cuts," Econ. Geology, VII., 1912. pp. 143–144.

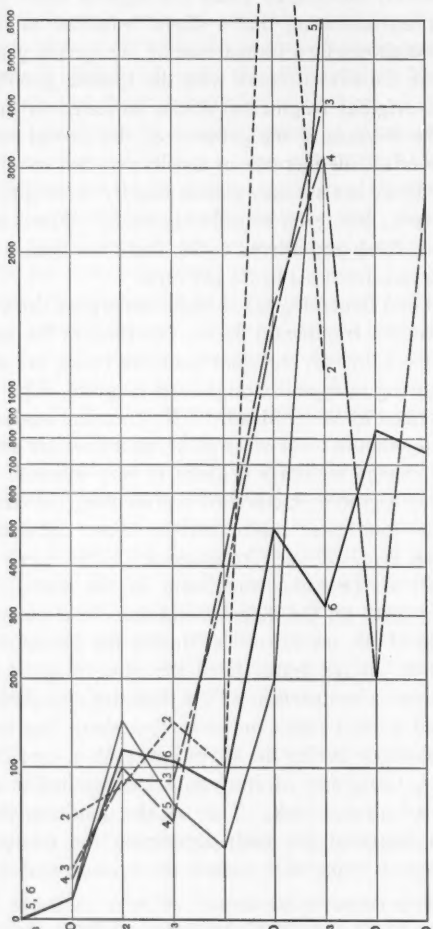


FIG. 15. Composite straight-line diagram, showing relative behavior of the oxide constituents of the dacite tuff during the formation of the quartz alunite (solid lines), quartz-pyrophyllite (dash lines), and quartz-sericite (dotted lines) rocks. Figures refer to the accompanying table.

stituent originally present in 100 grams of fresh rock, all of the constituents whose points fall to the right of 100.4 to 107.5, according to which altered rock is being considered, have decreased in absolute amount and the constituents whose points fall to the left have increased.

It is seen that the quartz-alunite rocks have increased in pyrite, sulphur, and sulphuric anhydride, and that all the rocks have increased in water, the quartz-sericite rocks much less than the other two types. All of the rocks have lost iron oxide, magnesia, and lime. It does not seem, however, as if the relative loss of these constituents in the different rocks is significant. All of the rocks have lost soda also, and in this case the relative loss is undoubtedly significant. The quartz-sericite rocks have lost the most and the quartz-alunite rocks, owing to the development of soda alunite, the least. The form in which a part of the soda is retained in the quartz-pyrophyllite rock is not known. It may be contained in sericite, but as these rocks contain less sericite than the associated quartz-sericite rocks, this seems doubtful. It is more probable that these rocks contain a small amount of unreplaced or secondary feldspar. The other oxides, silica, alumina, and potash, have increased in some rocks and decreased or remained nearly constant in others. It thus appears as if during alteration there was a rearrangement and slight transfer of these constituents, although they were not removed from the zone of alteration. The quartz-alunite rocks have lost some silica while the quartz-sericite rocks have gained a corresponding amount. In the quartz-pyrophyllite rocks silica has either remained constant or has increased slightly. As would be expected the quartz-pyrophyllite rocks have gained in alumina while the quartz-sericite rocks have lost. Also the rocks containing about 45 per cent. of alunite have gained in alumina but those containing a smaller amount, about 20 per cent., may have lost some alumina. The change in potash is especially characteristic, as it has increased in the quartz-alunite rocks, decreased in the quartz-pyrophyllite rocks, and remained nearly constant in the quartz-sericite rocks.

The original quartz in the dacite has not suffered any loss

TABLE SHOWING CHARACTER OF THE ALTERATION OF THE DACITE TUFF.

	No. 1	No. 2	$\frac{\text{No. 1}}{\text{No. 2}} \times 100$	No. 3	$\frac{\text{No. 1}}{\text{No. 3}} \times 100$	No. 4	$\frac{\text{No. 1}}{\text{No. 4}} \times 100$	No. 5	$\frac{\text{No. 1}}{\text{No. 5}} \times 100$	No. 6	$\frac{\text{No. 1}}{\text{No. 6}} \times 100$
SiO_2	73.22	87.80	83.4	81.94	89.4	71.88	102	48.82	150	62.70	117
Al_2O_3	13.46	9.08	148	15.29	88.2	23.56	57.1	19.08	70.6	12.68	106
Fe_2O_3	2.33	.40	1,120[1]	.11	4,050	.14	3,180	.07	6,380	1.40	319
FeO	.96	n.d.	.....	n.d.	.....	trace	.....	n.d.	.....	trace	.....
FeS_2	.....	.....	.....	.....	.....	.....	.....	.....	.....	2.69	0
MgO	.42	n.d.	.....	n.d.	.....	.21	200	n.d.	.....	.05	841
CaO	1.50	n.d.	.....	n.d.	.....	.06	2,500	n.d.	.....	.20	750
Na_2O	5.46	.02	27,300	.40	1,370	.36	1,520	2.74	199	1.09	499
K_2O	1.74	1.70	102	.50	348	.43	405	4.40	40.5	2.10	82.9
H_2O	.62	1.04	59.6	2.40	25.8	3.24	19.1	7.00	8.9	7.15	8.8
TiO_2	.28	n.d.	.....	n.d.	.....	n.d.	.....	n.d.	.....	n.d.	.....
P_2O_5	.10	n.d.	.....	n.d.	.....	n.d.	.....	n.d.	.....	n.d.	.....
MnO	trace	n.d.	.....	n.d.	.....	n.d.	.....	n.d.	.....	n.d.	.....
SO_3	trace	trace	.....	trace	.....	trace	.....	17.32[2]	0	7.06[2]	0
S	.....	.....	.....	.....	.....	.....	.....	.57[2]	0	2.88[2]	0
	100.09	100.04	.....	100.64	.....	99.88	.....	100.00	.....	100.00	.....
Specific gravity of non-porous rock	2.70	2.75	.....	2.76	.....	2.91	.....	2.75	.....	2.84	.....
Specific gravity of porous rock	2.68	2.70	.....	2.73	.....	2.88	.....	2.69	.....	2.79	.....
Porosity, per cent.	.67	1.8	.....	1.2	.....	1.0	.....	2.1	.....	1.8	.....
No. of grams of non-porous, altered rock derived from 100 gm. of non-porous fresh rock	.....	101.9	.....	102.2	.....	107.8	.....	101.9	.....	105.2	.....
No. of grams of porous, altered rock derived from 100 gm. of porous fresh rock	.....	100.7	.....	101.9	.....	107.5	.....	100.4	.....	104.1	.....

	No. 1	No. 2	$\frac{\text{No. 1}}{\text{No. 2}} \times 100$	No. 3	$\frac{\text{No. 1}}{\text{No. 3}} \times 100$	No. 4	$\frac{\text{No. 1}}{\text{No. 4}} \times 100$	No. 5	$\frac{\text{No. 1}}{\text{No. 5}} \times 100$	No. 6	$\frac{\text{No. 1}}{\text{No. 6}} \times 100$
Mineral composition:											
Quartz	30	82	.....	50	.....	20	.....	36	.....	58	.....
Feldspar	60	.....	.....	7.8	.....	8	.....	18.3	.....	10.3	.....
Sericite	2	14	.....		.....		.....		.....		.....
Kaolin	.....	3	.....	.....	.....	.....	.....		.....		.....
Pyrophyllite	.....	.....	.....	42	.....	71	.....	.....	.....	.....	.....
Alunite	.....	.....	.....	.....	.....	.....	.....	45	.....	20	.....
Diaspore	.....	.....	.....	.....	.....	.....	.....	.....	.....	4.5	.....
Magnetite and ilmenite	2	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Pyrite	.....	.....	.....	.....	.....	.....	.....	.....	.....	2.7	.....
Hematite and leucoxene	2	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Limonite	.....	1	.....	.2	.....	.2	.....	.1	.....	1.6	.....
Sulphur	.....	.....	.....	.....	.....	.....	.....	.6	.....	2.9	.....
Epidote and chlorite	2	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Talc	.....	.....	.....	.....	.....	.7	.....	.....	.....	.....	.....
Calcite	2	.....	.....	.....	.....	.1	.....	.....	.....	.....	.....
	100	100	.....	100	.....	100	.....	100	.....	100	.....

No. 1, Dacite tuff, one mile southeast of Monteith bay; No. 2, Cherty quartz-sericite rock, quarry of B. C. Pottery Co., Monteith claim; No. 3, Pink to white, quartz-pyrophyllite rock, quarry of B. C. Pottery Co., Monteith claim; No. 4, White to grayish, quartz-pyrophyllite rock, quarry of San Juan Min. & Mfg. Co., Deertrail claim; No. 5, Pink to white, quartz-alunite rock, Morris claim; No. 6, Bluish gray, quartz-alunite rocks, Morris claim. All rocks from Kyuquot sound and analyzed by N. L. Turner of Dept. of Mines, Mines Branch, Ottawa.

[1] All iron in No. 1 calculated as Fe_2O_3.

[2] S and SO_3 not determined directly. Both were estimated together as SO_3, and relative amounts of S and SO_3 arrived at by calculation.

except in one doubtful case, the quartz-pyrophyllite rock containing 71 per cent. of pyrophyllite; and in this case the apparent loss may be partly accounted for by the conspicuous addition of material, chiefly alumina. It is probable that the original quartz has not been greatly affected by the alteration. On the other hand the original ferromagnesian or mafic minerals, now represented in the dacites by the secondary minerals, chlorite, epidote, hematite, and calcite, have been entirely decomposed and most of their constituents removed. It is clear that the secondary quartz, sericite, pyrophyllite, alunite, diaspore, and kaolin, making up most of the altered rocks is the result of the alteration of the feldspar. Pyrite, with its alteration products, limonite and sulphur, seems to have been introduced, as will be presently described, after the formation of most of the other minerals.

In addition to the facts given above the following are significant as indicating the nature of the alteration. The replaced volcanics are, as mentioned, of Triassic and Jurassic age and have suffered deep erosion, at least 3,500 feet since the uplift of the old erosion surface or peneplain which forms the plateau in the vicinity of Kyuquot sound; and during the development of the peneplain at least 1,000 feet, and doubtless very much more, possibly 4,000 feet, as the replaced volcanics occur about 7,500 feet below the top of the Vancouver volcanics. The altered rocks are cut by dikes of quartz-bearing diorite porphyry, and of andesite porphyry, which although similar in character to the original volcanics are not nearly so greatly altered; nor are they altered in the same manner, their principal secondary minerals being chlorite, epidote, sericite, quartz, and calcite. Hence it seems clear that the alunitization and pyrophyllitization of the volvanics took place before the injection of the dikes. It appears from a microscopic examination of their texture that the altered rocks were impregnated and partially replaced by pyrite after the alunitization and pyrophyllitization. The alunite and pyrophyllite rocks are localized in their occurrence, for although similar pyritic volcanics occur in great profusion over Vancouver island, many of them highly altered, no other alunite or pyrophyllite rocks are

known. Not only are such rocks unknown in other portions of Vancouver island, but even at Kyuquot sound the deposits appear to be restricted to the vicinity of the intrusive feldspathic quartz diorite. It is thus assured that the solutions causing the alunitization and pyrophyllitization were of local origin and were not descending oxidizing waters of meteoric origin.

On the other hand the difference between the surface rocks and those found near or below ground-water level indicates that descending oxidizing solutions have been effective in forming limonite, sulphur, and kaolin, which are to some extent clearly pseudomorphic after pyrite. Both the limonite and sulphur have apparently been derived by the breaking up and oxidation of the pyrite, although sulphur occurs only in the alunite rocks. The kaolin has probably formed through the action of sulphuric acid derived by the oxidation of the pyrite. In addition, it appears, from the analyses of the samples collected by the writer, as if the surface rocks contain more alunite than the rocks at or below ground-water level; and it is possible that the additional alunite also was the result of the action of sulphuric acid in the descending meteoric waters. However, Mr. R. J. Wally, formerly chemist of the San Juan Mining and Manufacturing Co., states that his investigations indicate that the lower, bluish gray alunite rocks contain more alunite than the surface reddish to white rocks; and he believes that alunite as well as pyrite has been leached from the surface rocks.[16]

The apparent restriction of the altered rocks to the vicinity of the intrusive feldspathic quartz diorite and the very great erosion that the volcanic rocks associated with the alunite and pyrophyllite deposits have suffered, at least 4,500 feet, suggests that the alteration was caused by hot ascending solutions of deep-seated origin, which emanated from the intrusive batholith. Only two geologists, E. S. Larsen[17] and F. C. Schrader,[18] have had the

[16] Personal communication.

[17] "Alunite in the San Cristobal Quadrangle, Colo.," Bull. U. S. Geol. Survey, No. 530–F, 1912, p. 7.

[18] "Alunite in Patagonia, Arizona, and Bovard, Nevada," Economic Geology, Vol. VIII., 1913, p. 756 and pp. 764–765.

temerity to suggest that alunitization might be caused by ascending sulphuric acid solutions of deep-seated, rather than of comparatively shallow, solfataric, origin. However, Schrader states that the alunite at Patagonia might as well have been formed by the meteoric process; although he believes that the alunite at Bovard was deposited by magmatic solutions which emanated from Tertiary volcanic intrusives, that have been eroded in places for at least 2,000 feet. Larsen also states that evidence in his district was not sufficient to justify the assumption of ascending deep-seated sulphuric acid solutions, in view of the fact that geologists do not generally admit the presence of such solutions. Neither does it seem to the writer that the evidence in the Kyuquot Sound district is strong enough to support the view that all the alteration took place in this manner, although there can be little question that the rocks were somewhat altered following the intrusion of the feldspathic quartz diorite. The zone of quartz-sericite-chlorite rock in contact with the quartz diorite suggests that it and similar rocks were developed at that time. It is probable that at the same time the pyritization and possibly some of the silicification of the volcanics took place. However, as noted, the pyritization apparently followed the alunitization and pyrophyllitization. In addition it is certain that the alunitization and pyrophyllitization preceded the injection of the dikes of quartz bearing diorite porphyry, apparently an apophysial phase of the feldspathic quartz diorite, and of andesite porphyry. As already mentioned, the origin and time of injection of the andesite porphyry dikes are doubtful, but apparently some of the dikes are related to the volcanics and may be considered as injected equivalents. If this is true, the alunitization and pyrophyllitization and part of the silicification and sericitization was accomplished by solfataric action during the eruption of the volcanics. Since the alunite and pyrophyllite are probably developed only under moderate conditions of pressure and temperature, such as exist near the surface,[19] although alunite may form through a vertical range of

[19] Emmons, W. H., "Genetic Classification of Minerals," ECONOMIC GEOLOGY, Vol. 3, 1908, pp. 611–625.

at least several hundred feet,[20] the alunitization and pyrophyllitization of the volcanics doubtless took place before the altered volcanics were buried by the 4,500 feet and more of volcanics, which have been stripped away by erosion, reëxposing the alunitized and pyrophyllitized volcanics. That the alunite and pyrophyllite were formed near the surface is indicated also by the extremely fine-grained and even microcryptocrystalline, opal-like, character of the associated quartz, a feature which is characteristic of deposits formed near the surface.[21]

It is doubtful whether the sulphuric acid which was added to the volcanics was derived by oxidation, near the surface, of hydrogen sulphide, or was contained in the ascending hot waters. The deposits are not exposed through a great enough vertical distance to indicate whether or not they change rapidly within a shallow vertical range. In either case the deposits were formed near the surface during the eruption of the volcanics, and it is doubtful if, during eruption, the volcanic rocks suffered any great amount of oxidation and weathering by descending oxidizing meteoric waters; at least no other possible occurrences of such rocks are known in the Vancouver volcanics. Neither are the altered rocks as porous as they probably would be if they had been altered by descending acid solutions. It is therefore assumed that the deposits were formed, as most alunite deposits in the United States are believed to have been formed, by hot ascending acid solutions of volcanic origin and that at least those solutions causing alunitization carried free sulphuric acid.

The occurrence in separate masses of the three different types of altered rocks, quartz-alunite, quartz-pyrophyllite, and quartz-sericite rocks, that are all believed to have been formed by hot, ascending, acid solutions may be explained in several ways, all of which may have been effective, by a variation in the character of the ascending solutions, during different stages of solfataric action, perhaps caused by oxidation near the surface; by slight differences in either the chemical or physical character of

[20] Butler, B. S., and Gale, H. S., "Alunite, a Newly Discovered Deposit near Marysvale, Utah," Bull. U. S. Geol. Survey, No. 511, 1912, p. 37.

[21] Lindgren, Waldemar, "Mineral Deposits," 1913, p. 434.

the replaced volcanics; or by the loss of free sulphuric acid during the alunitization of a portion of the volcanics and the subsequent pyrophyllitization and sericitization of the volcanics somewhat farther away from the source of the solutions or from their main channels of circulation. However, as previously noted, there seems to have been a rather free interchange and transfer of materials throughout the altered zone. Since the three types of altered rocks are surrounded by quartz-sericite-chlorite rocks, it seems as if these were partly the result of the alteration of the volcanics at some distance from the channels of circulation by the somewhat cooler and less active solutions. However, as noted, the quartz-sericite-chlorite rocks are in part the result of alteration under deep-seated conditions following the intrusion of the granodiorite batholith and its attendant peripheral phases and minor intrusives. The occurrence of some of the quartz-sericite-chlorite rocks suggests that the deep-seated solutions which emanated from the intrusives followed the zones of previous alteration, as is indicated also by the more general pyritization of the altered rocks than of the comparatively fresh volcanics. As noted the altered rocks were still further altered by descending, oxidizing, meteoric solutions.

DISCUSSION

This department has been established by the editors in order to afford to those interested in questions relating to economic geology an opportunity for informal discussion. Contributions are cordially invited either in the form of discussion of more formal papers appearing in earlier numbers or bearing upon matters not previously treated. Letters should be directed to the Editor, Sheffield Scientific School of Yale University, New Haven, Conn. The full name of the author should be attached to all communications.

THE ORIGIN OF KAOLIN:

AN INTRODUCTION TO A DISCUSSION.

During the last twenty years considerable attention has been given by geologists and mineralogists to the origin of kaolin. Much has been done by American mining geologists to clear up this subject, but their conclusions are mainly contained in reports on mining districts and have, therefore, not commanded adequate attention. The data regarding the origin and properties of kaolin are also widely scattered in chemical, geological, agricultural and ceramic literature, so that it has become exceedingly difficult to obtain a full knowledge of the subject. Short time ago an article was published by H. Stremme, entitled "Die Chemie des Kaolins" in the annual entitled *Fortschritte der Mineralogie, Krystallographie u. Petrographie,* Vol. 2, 1912, and still more recently the manual of Mineral Chemistry, published by Professor Doelter, has reached this subject. In this manual, which also includes Stremme's article, a great amount of information is contained concerning the kaolin minerals.

The discussion in Germany was opened by H. Rösler, who in 1908 published a long and important paper in which he held that kaolin is not formed by weathering, but only by the action of thermal waters, or pneumatolytic processes. These statements were vigorously disputed, and Stremme among others proved beyond doubt that certain large deposits of kaolin, for instance,

those of Meissen in Saxony, were decidedly products of weathering.

It is not likely that any American geologist disputes the statement that kaolin may be formed by weathering. Professor Heinrich Ries has done much to clarify our ideas on this subject. Regarding the occurrence of kaolin in mineral deposits and mineralized zones, opinions are as yet divided.

I have always believed that kaolin does not ordinarily form in deposits which are formed by igneous emanations or by ascending thermal waters, except possibly very close to the surface where admixture with atmospheric waters is effected. In brief, kaolin is never a high temperature mineral, but is either a product of alteration by descending waters containing sulphuric acid or carbon dioxide, or of alteration by ascending weak carbonated waters close to the surface. That this opinion is not universally accepted is shown, for instance, by a sentence in Professor Tolman's review on my book on "Mineral Deposits," in which he says:[1]

> "This conclusion (regarding the origin of kaolin) may well be considered an expression of (the author's) personal opinion and lacks proof."

While perhaps not able to furnish absolutely convincing proofs, I would at least like to show that this opinion is supported by a strong array of evidence.

When speaking of kaolin, I refer to the silicate, Al_2O_3, $2SiO_2$, $2H_2O$, which is always crystalline, though rarely found as well defined crystals, and which has a remarkably constant chemical composition, the formula requiring 39.5 per cent. Al_2O_3, 46.5 per cent. SiO_2, and 14 per cent. water. Except for one experiment by Collins, in which hydrofluoric acid was used, the mineral has never been obtained by synthesis. Kaolin is decomposed by sulphuric acid. Besides kaolin we have several other hydro-silicates of alumina, such as halloysite and allophane. These contain much more water than kaolin, are amorphous, probably the result of hardening of colloids, and they are soluble in hydrochloric acid, which has practically no effect on kaolin.

Kaolin loses some of its water by treatment in exsiccator, or

[1] ECON. GEOL., Vol. 9, p. 200.

by drying at 125°. The larger part of the water is, however, given off at temperatures from 470°–500°. A small amount of water is tenaciously held and only given off at red heat. It is held by Stremme that dissociation of Al_2O_3 and SiO_2 takes place at 500°; and that at still higher temperatures and under atmospheric pressure these two compounds may reunite to sillimanite.

Another important property of kaolin is its ability to absorb bases, such as copper from a solution of silicate, while a corresponding amount of the bases of the kaolin is given off.

From these data it is first of all clear that kaolin cannot be formed, at or near the surface of the earth at a temperature of 470° or higher.

The conclusions regarding the absence of kaolin in ore deposits have been arrived at through the study of a great number of occurrences. This inductive evidence is undoubtedly very strong. At or near the outcrops of ore bodies kaolin is often found in large amounts. As mining operations reach lower levels the kaolin disappears, and at the water level, or at least a short distance below it, it is found that the soft, white material often so abundant both in ores and adjacent country, is not kaolin but finely divided muscovite, that is, sericite. It is natural that only those actively interested in mining geology would fully appreciate this change of kaolin to sericite in depth. This certainly applies to all veins which have been formed in the vicinity of intrusive masses shortly after the intrusion, and it probably applies also to veins formed near the surface, although the presence here of kaolin as a primary mineral cannot be denied in the same emphatic manner. The result of inductive reasoning is then that the agencies which produce mineral deposits—in the majority of cases heated waters under high pressure—are not capable of developing kaolin from the aluminum silicates of the rocks. On the other hand, when sericite is exposed to weak sulphuric acid waters in the oxidized zone, perhaps also to other kinds of surface waters, a leaching of potash takes place and the sericite is converted to kaolin. If the solutions are strongly acidified the kaolin itself will be decomposed. It is, in fact, recognized by many chemists that the

sericitic alteration is an intermediate stage towards ultimate kaolinization. According to experiments by Cameron and Bell potassium is more easily extracted from muscovite by ordinary or carbonated waters than from orthoclase.

In reading the literature recently compiled by Mr. Stremme my attention was attracted to a number of Lemberg's experiments dealing with the action of salt solutions on kaolin. These experiments which were later in part repeated by Thugutt. It was shown that solutions of potassium and sodium salts when allowed to act on kaolin at a temperature of from 100° to 200° C. converted the kaolin to alkaline silicates similar to sodalite, nephelite, or analcite. Some of these compounds were obtained in crystalline form. Thus, kaolin is not stable when heated in strong alkaline solutions at from 100° to 200° in closed vessels. One of the solutions used by Lemberg contained, for instance, 15 per cent. sodium chloride, and 5 per cent. sodium carbonite. We have now then a good physico-chemical reason why kaolin does not form in, or close to, mineral deposits, which originate at temperatures above 100°. In all such cases the active solutions, similar to most of our thermal waters, contained a large amount of alkalies, and consequently hydrous alkaline silicates like sericite would be formed instead of kaolin.

Regarding the development of kaolin at temperatures below 100°, we have little available information. It seems clear, however, that at ordinary temperature weak alkaline waters, such as the ordinary surface waters, are not competent to transform kaolin into sericite, and it is questionable also whether within limited time strong solutions, such as sea water, could effect a change in the kaolin.

Some investigations have been undertaken tending to prove that in the vents of hot springs, rich in alkalies, sericite-like minerals, such as pinite, form from feldspathic materials. The granite fragments in the vents of the Carlsbad springs are transformed to such material and not to kaolin. On the other hand, there are abundant data to show that weak and cold mineral waters when rich in carbon dioxide tend to produce kaolin from feldspar rather than sericite.

Whether kaolin or sericite will form from thermal waters at, or near the surface, is probably a question of temperature and concentration of the waters. We have one very definite statement tending to show that kaolin can be formed under such circumstances. In the vicinity of Teplitz in Bohemia some of the porphyries of the region are altered by the hot springs, and the altered rocks contain fine-grained quartz, barite, and much fluorite.[2]

In examining some of these rocks F. Cornu[3] found that the feldspars in porphyries altered by thermal waters are converted into aggregates of minute kaolin plates. The mineral was definitely identified.

Whether it is possible that kaolin may form at higher temperatures and pressures in the presence of waters which contain little or no alkalies is a question that must be left open, and which so far has not been investigated. Such a mode of origin would seem to be highly improbable in case of a mineral which contains as much water as does kaolin. Moreover, it is practically certain that the solutions in all cases of ore deposits were rich in alkalies. Potassium and lithium micas are, for instance, characteristic of tin deposits, which probably were formed at the temperature of about 500°, and it seems extremely unlikely that any kaolin could be developed simultaneously with the minerals characteristic of the tin veins. It is well known, of course, that subsequent alteration develops kaolin from some minerals of this series, from topaz for instance.

I realize fully the possibilities of errors in these tentative generalizations; this communication has, in fact, been written in the hope of eliciting comments and suggestions from those interested in the subject of kaolin and sericite.

WALDEMAR LINDGREN.

BOSTON, MASS.,
October 28, 1914.

[2] Hibsch, J. E., *Tsch. M. u. P. Mitt.*, 25, 1906, pp. 482–488.
[3] *Tsch. M. u. P. Mitt.*, 25, 1906, pp. 234.

REVIEWS

Text-Book of Petrology. Vol. I. The Petrology of the Igneous Rocks. Seventh edition, revised. By F. H. HATCH, PH.D. George Allen and Co., Ltd., London.

The seven editions through which Hatch's "Text-Book of Petrology" has passed in the twenty-two years since the first edition appeared is of itself evidence that the book fills an important place as an elementary text-book of petrology. In the present (seventh) edition, Vol. I., the "Petrology of the Igneous Rocks" covers the field of the former editions, and Vol. II., the "Petrology of the Sedimentary Rocks" by Hatch and Rastall, is entirely new. As the author states in his preface "the two volumes now constitute a complete, if necessarily brief, survey of the whole science of rocks, not only in regard to their composition and structure, but also in respect to their origin and metamorphism." On the whole the volumes are probably the most consistently elementary English text-books which cover practically the whole field of Petrology.

This edition has undergone considerable revision and new chapters on the Pyroclastic Rocks and the Metamorphic Derivatives of the Igneous Rocks have been added, together with numerous new figures.

On the whole the book is clear and well written but a few criticisms may not be amiss. In the list of General Works of Reference on page xxiii, the references are to old editions of Clarke's "Data of Geochemistry" and to Iddings's "Rock Minerals" although new, completely revised editions have been published.

The repeated use of "acid rocks" and "basic rocks" and of "acid feldspar" although it conforms to the common usage in Europe and, to a less extent in America, is to be deplored since chemists insist that neither rocks nor feldspar are in any sense acid or basic. The terms sodic and calcic for the feldspars, and silicious and subsilicious for the rocks, are much more accurate and expressive.

In chapter III on "Texture and Microstructure" the discussion of the highly important subject of the application of the physical-chemical laws to the crystallization of a magma is not entirely clear or satisfactory. It is a very difficult subject to treat in so brief and elementary a way.

In the classification of the Igneous Rocks in part III., the author subdivides the rocks into (1) Acid Group, with silicia content above 66 per cent.; (2) Intermediate, with silicia content between 66 and 52 per cent.; (3) Basic, with silicia content below 52 per cent.

He further subdivides them according to their feldspar or feldspathoid into the alkali series, monzonite series, and calc-alkali series. In the opinion of the reviewer, this highly arbitrary scheme, in part chemical, in part mineralogical, is open to serious objections.

The present edition should have as important a place as an elementary text-book of petrology, as the former editions.

ESPER S. LARSEN.

Manual of Petrographic Methods. By ALBERT JOHANNSEN, PH.D. McGraw-Hill Book Company, Inc., 239 West 39th Street, New York. 1914. Price, $3.00 net.

Professor Johannsen's manual will be welcomed by all investigators and teachers of petrography and optical mineralogy as the first treatise in English which deals with the subject of optical methods with the completeness of the German treatises of Rosenbusch and Wulfing and Groth. Moreover, the incorporation of the numerous and important methods which have appeared in the last few years has made this manual the most up-to-date treatise on the subject. The book appears at an opportune time since the importance of measuring the optical constants for the accurate and rapid determination of minerals is being more and more appreciated not only by petrographers but by economic geologists, and all engaged in the precise determination of minerals or in the study of mineral aggregates.

The manual deals primarily with the methods of optical mineralogy, especially as applied to the petrographic microscope and its accessories. It also contains chapters on mineralogical principles, stereographic projection, determination of specific gravity, mechanical separation of minerals, microchemical reactions, the preparation of thin sections, and the collection and care of petrographic specimens.

It contains the most complete and up-to-date descriptions of the petrographic microscope and its accessories and of the methods of using them to measure the optical constants of a mineral. However, it is, perhaps, not sufficiently critical, and the student or investigator would hardly be able from the manual always to select the instruments and methods most suited to any particular investigation. Moreover, the author has failed to describe a number of instruments and methods, perhaps not closely related to the petrographic microscope, even though they are far superior in accuracy and in nearly all other respects, to any of the more purely microscopic methods. As illustrations may be mentioned the total refractometer for measuring indices of refraction both of minerals and liquids, the prism methods of measuring indices of refraction and the axial angle apparatus.

The book is well printed and contains a large number of excellent illustrations. Few typographic errors were noticed by the reviewer, however, on page 617 Bolivia and Brazil are placed under Austria-Hungary.

The book is an important contribution to petrography and optical mineralogy and should be in the hands of all advanced workers in those sciences, especially petrographers, economic geologists and mineralogists.

ESPER S. LARSEN.

A Text-Book of Geology, for use in mining schools, colleges and secondary schools. By JAMES PARK, Professor of Mining in the University of Otago, New Zealand. Charles Griffin & Co., London, 1914. 8vo, pp. 598, figs. 264, Plates 70.

This volume is designed "to cover the requirements in Geology as now defined for Engineering, Mining, and Agricultural Schools and Colleges." To the reviewer it seems exceptionally well adapted for a one-year course for engineering and mining students, but it is believed to be too advanced for secondary schools and to lay less stress upon surface features and phenomena than is desirable in the instruction of agricultural students. The volume is written by an economic geologist of wide experience and broad sympathies, and throughout bears evidence of a utilitarian viewpoint of the general subject. Theoretical considerations are accorded but small space although current theories and conceptions are briefly stated. The causes of glaciation, igneous activity, metamorphism, and diastrophism are rapidly passed by but the observed facts are rather fully presented. In this respect the treatment is quite different from Le Conte's "Elements" and particularly from Chamberlin and Salisbury's "College Geology" which keep constantly before the reader the bearing of observed facts upon the fundamental conceptions of the science.

In the first chapter seventeen basic principles, including the origin of the earth, extent of geologic time, geologic history, and the action of modifying agencies, are presented in twelve pages. Here the author mentions several conceptions of earth genesis, apparently subscribing to the nebular hypothesis. Following are chapters devoted to the agencies of aggradation and degradation, rock structures, earth movements, etc., finally leading to a chapter on rock-forming minerals. This is followed by chapters on sedimentary, igneous, and metamorphic rocks. Part I closes with a chapter on conformity and unconformity, which follows one on fossils.

About one-third of the volume comprising Part II is devoted to stratigraphical geology. Each of the systems is accorded broad treatment and

sections are given for the better known localities on each of the continents. Plates of fossils illustrate the life of each great time division. The presentation is excellent and should serve to stimulate in the student the breadth of view essential to an adequate conception of geologic principles.

Part III includes a chapter of 33 pages in which is condensed a vast amount of information on mineral deposits and an excellent chapter of 13 pages on the elements of field geology and geological surveying. Two brief appendices on details of geologic methods, followed by a classified bibliography of the more important reference books on geology and a comprehensive index, close the volume.

A commendable feature of the presentation is brief summaries at the end of each chapter. In general the volume is characterized by statements of facts rather than by discussions of principles, is well written, and is admirably illustrated. It is believed to be worthy of careful examination by anyone teaching a one-year course in geology to engineering students and will have no small use as a reference book, although in this respect it may be wished that more emphasis had been laid upon the geology of Australasia, the author's principal field of activity.

J. B. UMPLEBY.

SCIENTIFIC NOTES AND NEWS[1]

THE annual meeting of the Canadian Mining Institute was held in Toronto March 3, 4, and 5. The following papers of interest to ECONOMIC GEOLOGY were presented: J. A. Van Mater, "The Zinc Industry in America"; H. E. T. Haultain, J. M. Bell and J. E. Hardman, "The Stimulation of Prospecting"; E. T. Corkill, "Safety Engineering at the Canadian Copper Company's Works and Mines, Copper Cliff, Ont."; O. B. Perry, "Dredging Industry in the Yukon"; D. D. Cairnes, "The Economic Possibilities of the Yukon"; Frederic Keffer, "The Ore Deposits of the Copper Mountain, Similkameen, B. C."; Bradley Stoughton, "The Smelting of Titaniferous Ores in the Blast Furnace"; R. A. A. Johnson, "Certain Canadian Minerals for which a Demand has been Created as a Result of the War"; J. B. Tyrell, "Gold on the North Saskatchewan River"; E. L. Bruce, "The Beaver Lake Gold District"; F. D. Adams, "The Conservation of our Mineral Resources"; D. B. Dowling, "The Alberta Oil Fields"; S. J. Schofield, "The Ore Deposits of the Ainsworth Mining Camp."

THE San Francisco meeting of the American Association for the Advancement of Science will be held August 2–7 at the University of California and at Leland Stanford Jr. University. The Geological Society of America will have charge of the program of the geological section.

ROSWELL H. JOHNSON and L. G. Huntley have opened an office in Pittsburgh for undertaking examinations and reports on oil and gas properties.

[1] Geologists, mining engineers and others interested in applied geology are invited to keep the editor informed of new investigations of mining districts or scientific studies undertaken by them, together with such other scientific and personal items as may come to their notice.

THE International Mining Congress will be held in San Francisco, September 20–25. Col. G. W. Goethals will act as honorary president, and is expected to preside over the general sessions.

RALPH ARNOLD, geologist and petroleum engineer, was elected to the board of trustees of Stanford University, January 29. Mr. Arnold is now consulting engineer of the city of Los Angeles.

THE New York meeting of the American Institute of Mining Engineers was held February 15–17. The following papers of interest to ECONOMIC GEOLOGY were presented: Edward G. Norton, "The Origin of the Louisiana and East Texas Salines"; W. B. Phillips, "Investigation of Sources of Potash in Texas"; Thomas L. Watson and J. Sharshall Grasty, "Barite of the Appalachian States"; N. B. Davis, "The Plasticity of Clay and Its Relation to Mode of Origin"; Charles H. MacDowell, "German and Other Sources of Potash Supply"; Joel H. Watkins, "White Burning Clays of the Southern Appalachian States"; Joseph H. Pratt, "Minerals Used in Manufacture of Lighting Apparatus"; James F. Kemp, "The Mayari Iron-Ore Deposits, Cuba"; Douglas Bunting, "The Limits of Mining Under Heavy Wash"; Charles T. Malcolmson, "Recent Developments in Coal Briquetting"; Philip W. Henry, "Depreciation as Applied to Oil Properties"; Roswell H. Johnson, "The Role and Fate of the Connate Water in Oil and Gas Sands"; Alfred H. Broods, "The Petroleum Fields of Alaska"; C. W. Washburne, "The Estimation of Oil Reserves."